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Management and Disposition of Excess Weapons Plutonium

Committee on International Security and Arms Control
National Academy of Sciences

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PANEL ON REACTOR-RELATED OPTIONS FOR THE DISPOSITION OF EXCESS WEAPONS PLUTONIUM

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Preface

With the end of the Cold War, the United States and the nations of the former Soviet Union are engaged in arms reductions on an unprecedented scale. What to do with the materials from the tens of thousands of nuclear weapons to be dismantled has become a pressing problem for international security. This study results from a request to the National Academy of Sciences' Committee on International Security and Arms Control (CISAC) by General Brent Scowcroft, then the National Security Adviser to President Bush. Scowcroft asked for a full-scale study of the management and disposition options for plutonium after hearing a CISAC briefing on its discussions in March 1992 with a counterpart group from the Russian Academy of Sciences. The Clinton administration confirmed CISAC's mandate in January 1993.

The formal U.S. government sponsor of the report is the Office of Nuclear Energy of the Department of Energy (DOE). Additional support for the project is being provided by the John D. and Catherine T. MacArthur Foundation and National Research Council funds. The MacArthur Foundation and the Carnegie Corporation of New York provide core support for CISAC, including its policy reports.

CISAC is a standing committee of the academy, unlike most National Research Council committees, which are formed to conduct a particular study and then dissolved. Established in 1980 to bring the scientific and technical capabilities of the academy to bear on problems of international security, CISAC's members include distinguished scientists, engineers, and policy experts. CISAC's objectives are to (1) engage similar organizations in other countries in discussions of international security and arms control policy; (2) develop recommendations and other initiatives on scientific and technical issues related to international security and arms control; and (3) respond to requests for analysis and information from the government. John P. Holdren (Class of 1935 Professor of Energy, University of California-Berkeley) serves as chair, with Catherine McArdle Kelleher (Senior Fellow, The Brookings Institution) as vice-chair.

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CISAC's former chair, Wolfgang K.H. Panofsky (Professor and Director Emeritus, Stanford Linear Accelerator Center, Stanford University), chairs the plutonium study project. With the exception of Joshua Lederberg, who was unable to participate in the project, all members of CISAC took part in the study and have unanimously endorsed this report.

In carrying out its study, CISAC focused on the substantial security risks posed by these excess nuclear weapons and materials. The committee examined the stages of the reductions process, beginning with dismantlement of nuclear weapons, continuing through intermediate storage of the fissile materials from those weapons, and ending with long-term disposition of those materials. The committee focused specifically on the political and institutional context of these steps, both nationally and internationally. The committee has attempted to evaluate the consequences of each step for enduring, stable nuclear arms reductions and for improving the prospects for nuclear nonproliferation.

One important set of options would introduce the plutonium into nuclear reactors or into the waste stream from nuclear reactors. In order to supplement the committee's technical expertise for examining these options, CISAC formed a small Panel on Reactor-Related Options for the Disposition of Excess Weapons Plutonium, headed by John P. Holdren, to evaluate and make recommendations to the committee. The panel report, which is being published as a companion volume, was subject to a separate peer review by the National Academy of Sciences.

The study proved to be a huge undertaking, demanding hundreds of hours of research, discussion, and drafting from committee and panel members who were operating under a tight schedule to produce the report in time to be most valuable for U.S. policymaking. The committee and the panel received dozens of briefings from U.S. government and private experts, visited sites in the U.S. nuclear weapons production complex, and traveled to Russia, where they met with major figures involved in formulating that country's policy on disposition.

The CISAC staff provided invaluable assistance throughout the course of the study. Study Director Matthew Bunn, who supported both the committee and the panel reports, deserves special recognition. Not only did he draft much of the full committee report, and portions of the panel report, he also coordinated the effort and did research on key issues that greatly enriched the study. Mr. Bunn produced prodigious quantities of work in amazingly short time and made major intellectual contributions to the study's development. It could not have been completed without him.

CISAC's staff director, Jo Husbands, also deserves recognition. She provided crucial guidance and support throughout the study, with unfailing intelligence and unflappable good humor. She also kept the committee's other projects on track while the study was under way. Lois Peterson and Monica Oliva, CISAC's research associate and research assistant, respectively, labored long and hard to provide both substantive and administrative assistance, including much of the work of preparing the manuscript for publication. La'Faye

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Lewis-Oliver, CISAC's Administrative Assistant, provided essential administrative support throughout the process.

The issue of management and disposition of plutonium from arms reductions has a long history and a voluminous literature, stretching back almost to the beginning of the nuclear age. In recent years, these issues have been studied by a wide variety of groups and individuals in the United States, including those associated with the Department of Energy and other agencies of the U.S. government, the Office of Technology Assessment, the Natural Resources Defense Council, the Federation of American Scientists, the Center for Science and International Affairs at Harvard University, the Institute for Energy and Environmental Research, several Department of Energy laboratories, and a variety of private companies. Groups and individuals in Russia, Europe, Japan, and elsewhere have also examined the problem. In carrying out its study, CISAC benefited greatly from this substantial body of prior work, and extensive communications with many of those involved in it, for which the committee is profoundly grateful.

In addition, CISAC was fortunate to receive help from many parts of the Department of Energy. Staff members from DOE headquarters and facilities, including Hanford, Savannah River, Los Alamos, and Lawrence Livermore, generously gave time to help clarify and resolve technical issues, as well as providing access to relevant experts and materials. The Idaho National Engineering Laboratory merits particular recognition for its significant effort, without charge to the academy, to analyze several aspects of the reactor disposition options, such as nonfertile reactor fuels. Without this assistance, it would have been impossible for the committee to examine these issues in the depth required, with the time and personnel at its disposal.

Finally, but not least, CISAC received invaluable assistance from William G. Sutcliffe of Lawrence Livermore National Laboratory, who served as an unpaid consultant and an informal liaison to DOE for the project. His contacts and his own extensive knowledge of both the substance and the policy process for these issues were often indispensable.

There are no easy answers to the problems posed by the fissile materials that are part of the legacy of the Cold War arms competition between the United States and the former Soviet Union. As the committee makes clear in its study, the issues it addresses and the options it outlines and evaluates will be of critical importance to the future prospects for nonproliferation and arms reduction. Action is urgently needed, and the study is a road map to assist policymakers as they make these difficult choices. In CISAC's words, "The existence of this surplus material constitutes a clear and present danger to national and international security. None of the options yet identified for managing this material can eliminate this danger; all they can do is to reduce the risks."

Bruce Alberts

President, National Academy of Sciences

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Management and Disposition of Excess Weapons Plutonium

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Executive Summary

Under the first and second Strategic Arms Reduction Treaties (START I and II) and unilateral pledges made by Presidents Bush, Gorbachev, and Yeltsin, many thousands of U.S. and Russian nuclear weapons are slated to be retired within the next decade. As a result, 50 or more metric tons of plutonium on each side are expected to become surplus to military needs, along with hundreds of tons of highly enriched uranium (HEU). These two materials are the essential ingredients of nuclear weapons, and limits on access to them are the primary technical barrier to acquisition of nuclear weapons capability in the world today. Several kilograms of plutonium, or several times that amount of HEU, are sufficient to make a nuclear weapon.

The existence of this surplus material constitutes a clear and present danger to national and international security. None of the options yet identified for managing this material can eliminate this danger; all they can do is to reduce the risks. Moreover, none of the options for long-term disposition of excess weapons plutonium can be expected to substantially reduce the inventories of excess plutonium from nuclear weapons for at least a decade.

PRINCIPAL RECOMMENDATIONS

Our study of this problem leads us to the following four principal recommendations:

1. *A New Weapons and Fissile Materials Regime*. We recommend that the United States work to reach agreement with Russia on a new, reciprocal regime that would include:

(a) declarations of stockpiles of nuclear weapons and all fissile materials;
(b) cooperative measures to clarify and confirm those declarations;

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(c) an agreed halt to the production of fissile materials for weapons; and
(d) agreed, monitored net reductions from 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.

2. *Safeguarded Storage*. We recommend that the United States and Russia pursue a reciprocal regime of secure, internationally monitored storage of fissile material, with the aim of ensuring that the inventory in storage can be withdrawn only for non-weapons purposes.
3. *Long-Term Plutonium Disposition*. We recommend that the United States and Russia pursue long-term plutonium disposition options that:

(a) minimize the time during which the plutonium is stored in forms readily usable for nuclear weapons;
(b) preserve material safeguards and security during the disposition process, seeking to maintain the same high standards of security and accounting applied to stored nuclear weapons;
(c) result in a form from which the plutonium would be as difficult to recover for weapons use as the larger and growing quantity of plutonium in commercial spent fuel; and
(d) meet high standards of protection for public and worker health and for the environment.

The two most promising alternatives for achieving these aims are:

- fabrication and use as fuel, without reprocessing, in existing or modified nuclear reactors; or
- vitrification in combination with high-level radioactive waste.

A third option, burial of the excess plutonium in deep boreholes, has until now been less thoroughly studied than have the first two options, but could turn out to be comparably attractive.

4. *All Fissile Material*. We recommend that the United States pursue new international arrangements to improve safeguards and physical security over all forms of plutonium and HEU worldwide. In particular, new cooperative efforts to improve security and accounting for all fissile materials in the former Soviet Union should be an urgent priority.

Because plutonium in spent fuel or glass logs incorporating high-level wastes still entails a risk of weapons use, and because the barrier to such use diminishes with time as the radioactivity decays, consideration of further steps to reduce the long-term proliferation risks of such materials is required, regardless of what option is chosen for disposition of weapons plutonium. This global effort should include continued consideration of more proliferation-resistant

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nuclear fuel cycles, including concepts that might offer a long-term option for nearly complete elimination of the world's plutonium stocks.

On September 27, 1993, the Clinton administration announced a non-proliferation initiative that included some first steps in the directions recommended above, among them a proposal for a global convention banning production of fissile materials for weapons; a voluntary offer to put U.S. excess fissile materials under International Atomic Energy Agency (IAEA) safeguards; and a recognition that plutonium disposition is an important non-proliferation problem requiring renewed interagency, and ultimately international, attention. This is a much needed and timely start; more, however, remains to be done.

CRITERIA AND CONTEXT

The steps we recommend are designed to meet three key security objectives:

1. to minimize the risk that either weapons or fissile materials could be obtained by unauthorized parties;
2. to minimize the risk that weapons or fissile materials could be reintroduced into the arsenals from which they came, thereby halting or reversing the arms reduction process; and
3. to strengthen the national and international arms control mechanisms and incentives designed to ensure continued arms reductions and prevent the spread of nuclear weapons.

Other key criteria include protecting worker and public health and the environment; being acceptable to the public and the institutions whose approval is needed; and, to the extent consistent with other criteria, minimizing costs and delays.

We note that the expenditures implied by all our recommendations combined would total at most several billion dollars, spread over a period of a decade or decades. Since the primary objective is the reduction of major security risks, these expenditures should be considered in the context of the far larger sums being spent every year to provide national and international security. Thus, although the costs of alternate approaches are important and are discussed in the report, cost is not the primary criterion in choosing among competing options. Moreover, exploiting the energy value of plutonium should not be a central criterion for decision making, both because the cost of fabricating and safeguarding plutonium fuels makes them currently uncompetitive with cheap and widely available low-enriched uranium fuels, and because whatever economic value this plutonium might represent now or in the future is small by comparison to the security stakes.

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World Stocks of Fissile Materials

The problem of management and disposition of excess weapons plutonium must be considered in the context of the large world stocks of fissile materials. While all but a small fraction of the world's HEU is in military use, civilian stocks of plutonium are several times larger than military stocks and are growing much faster, by some 60 to 70 tons each year. Most of these civilian stocks, however, are in the form of radioactive spent fuel from the world's power reactors, from which the plutonium is difficult to extract. The difficulty of extracting this plutonium declines substantially as the radioactivity of the fuel decays over the decades after it leaves the reactor. Roughly 130 tons of plutonium have been separated from spent fuel for reuse as reactor fuel, of which some 80 to 90 tons remains in storage in separated form.

Plutonium customarily used in nuclear weapons (weapons-grade plutonium) and plutonium separated from spent reactor fuel (reactor-grade plutonium) have different isotopic compositions. Plutonium of virtually any isotopic composition, however, can be used to make nuclear weapons. Using reactor-grade rather than weapons-grade plutonium would present some complications. But even with relatively simple designs such as that used in the Nagasaki weapon—which are within the capabilities of many nations and possibly some subnational groups—nuclear explosives could be constructed that would be assured of having yields of at least 1 or 2 kilotons. Using more sophisticated designs, reactor-grade plutonium could be used for weapons having considerably higher minimum yields. Thus, the difference in proliferation risk posed by separated weapons-grade plutonium and separated reactor-grade plutonium is small in comparison to the difference between separated plutonium of any grade and unseparated material in spent fuel.

While plutonium and HEU can both be used to make nuclear weapons, there are two important differences between them. The first is that HEU can be diluted with other, more abundant, naturally occurring isotopes of uranium to make low-enriched uranium (LEU), which cannot sustain the fast-neutron chain reaction needed for a nuclear explosion. LEU is the fuel for most of the world's nuclear power reactors. In contrast, plutonium cannot be diluted with other isotopes of plutonium to make it unusable for weapons. "Re-enriching" LEU to the enrichment needed for weapons requires complex enrichment technology to which most potential proliferators do not have access, while separating plutonium from other elements with which it might be mixed in fresh reactor fuel requires only straightforward chemical processing. Thus, the management of plutonium in any form requires greater security than does the management of LEU.

Second, as noted earlier, in the current nuclear fuel market, the use of plutonium fuels is generally more expensive than the use of widely available LEU fuels—even if the plutonium itself is "free"—because of the high fabrication costs resulting from plutonium's radiological toxicity and from the security

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precautions required when handling it. As a result, while most of the world's roughly 400 nuclear reactors could in principle burn plutonium in fuel containing a mixture of uranium and plutonium (mixed-oxide or MOX fuel), few—and none in the United States—are currently licensed to do so.

The United States has agreed to buy 500 tons of surplus Russian HEU, blended to LEU, for $11.9 billion over the next 20 years, provided certain conditions are met. The United States will later resell the material to fulfill the demand for nuclear fuel on the domestic and world markets. While the purchase of Russian plutonium could, similarly, be justified on security grounds, both the security aspects and the economics of using plutonium as reactor fuel would be less attractive than in the case of LEU.

Because of the more difficult technical and policy issues involved, this report focuses primarily on the disposition of plutonium rather than HEU.

The International Environment

The management and disposition of plutonium from dismantled nuclear weapons will take place within a complex international context that includes the arms reduction and nonproliferation regimes of which this problem is an element, the continuing crisis in the former Soviet Union, worldwide plans for civilian nuclear energy (particularly the use of separated plutonium), and existing approaches to safeguards and security for nuclear materials.

Recent *nuclear arms reduction* agreements and pledges, along with national decisions concerning what stocks of plutonium are to be declared "excess," will largely set the parameters of how much plutonium will require disposition and when it will become available. The reductions agreements entail a complex and uneven schedule of reductions in deployed launchers between now and 2003. As yet, no agreement exists to govern the dismantlement of the surplus nuclear weapons, or the modes of storage and eventual disposition of the fissile materials, although discussions of some aspects of the problem are under way. Mutually agreed, monitored provisions for the disposition of fissile materials could help enhance political support for implementation of START II and for agreement on deeper reductions.

The current *crisis in the former Soviet Union* creates a variety of risks with respect to the management and disposition of nuclear weapons and fissile materials. We categorize these as dangers of:

- "breakup," meaning the emergence of multiple nuclear-armed states where previously there was only one;
- "breakdown," meaning erosion of government control over nuclear weapons and materials within a particular state; and
- "breakout," meaning repudiation of arms reduction agreements and pledges, and reconstruction of a larger nuclear arsenal.

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Breakup is the most immediate threat, mainly because of uncertainty over whether Ukraine will carry out its denuclearization pledges. Security concerns may well be the driving factors in Ukraine's ultimate decision, but that decision could be affected by measures that ensure that weapons and fissile materials transferred to Russia will not be reused for military purposes, and that provide compensation for these materials.

Breakdown of the elaborate system of control of nuclear weapons and fissile materials in the former Soviet Union remains a possibility, despite Russian efforts to maintain the former Soviet systems for this purpose. The thefts of conventional weapons and nuclear materials other than plutonium and HEU that have already occurred are disturbing. Enhanced assistance in improving security and accounting for fissile materials in the former Soviet Union is a potentially high-leverage area deserving urgent attention. The broad regime of accounting we recommend could provide an important basis for additional steps to improve security of these materials.

Breakout seems unlikely in the near term. The significant nuclear arsenals that each side will retain under START II will further reduce any motivation that a future Russian government might have for taking such a step. Ratification and implementation of START I and START II are not yet assured, however. The steps that we outline would reduce the potential for breakout, and provide a foundation for deeper reductions and for the inclusion of additional parties in the future.

The foundation of the *nuclear nonproliferation regime* is the Non-Proliferation Treaty (NPT), which is up for extension in 1995. Agreements for secure, safeguarded management and disposition of fissile materials from surplus nuclear weapons could help make clear that the nuclear powers are fulfilling their disarmament obligations under Article VI of the NPT. Moreover, acceptance by the major nuclear powers of safeguards and constraints on substantial portions of their nuclear programs would help to reduce the inherently discriminatory nature of the nonproliferation regime. These steps, while probably not dissuading all nations that might be attempting to acquire nuclear weapons, would help build global political support for indefinite extension of the NPT and strengthening the regime, which are major U.S. policy goals.

International efforts to reduce the proliferation risks posed by the existence of civilian plutonium and enriched uranium rest on *safeguards*, which are national and international measures designed to detect diversion of materials and enable a timely response, and *security*, which consists of (currently national) measures designed to prevent theft of materials through the use of barriers, guards, and the like. Standards for both vary widely. Those applied to civilian materials, even separated plutonium and HEU, are less stringent than those applied to nuclear weapons and fissile material in military stocks. Varying and lower standards may be justified in the case of spent fuel for the first decades outside the reactor, when its high radioactivity makes it difficult to steal or divert, but they are not justified in the case of separated civilian plutonium or

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HEU. New steps toward improved and consistent international standards should be pursued.

Choices regarding the fissile materials from dismantled weapons may also affect and be affected by *civilian nuclear power programs*, a topic that depends on economic, political, and technical factors outside the scope of this study. In some countries, nuclear power programs already include the use of plutonium in the fuel loaded into reactors. But the amount of weapons plutonium likely to be surplus is small on the scale of global nuclear power use—the equivalent of only a few months of fuel for existing reactors—and it is not essential to the future of civilian nuclear power. There is thus no reason that disposition of this weapons plutonium should drive decisions on the broader questions surrounding the future of nuclear power.

The production of tritium was not part of our charge, and we have not examined alternatives for this purpose in detail. We believe, however, that there is no essential reason why plutonium disposition and tritium production need be linked, and there appear to be good arguments why they should not be. Technically, the scale of the plutonium disposition task is very much larger than any tritium production requirement. From a policy perspective, producing weapons materials in the same facility that was destroying other weapons materials would raise political and safeguards issues.

THE PROPOSED WEAPONS AND FISSILE MATERIALS REGIME

We recommend a broad transparency regime for nuclear weapons and fissile materials, as outlined above. This regime could be approached step-by-step, with each step adding to security while posing little risk. The regime we envision would include a variety of measures applying to each phase of the life cycle of military fissile materials: production and separation of the materials; fabrication of fissile material weapons components; assembly, deployment, retirement, and disassembly of nuclear weapons; and storage and eventual disposition of fissile materials. These measures should be mutually reinforcing, to build confidence that the information exchanged is accurate and that the goals of the regime are being met.

There is likely to be some resistance to a regime of full accounting and monitoring of total weapons and fissile material stocks and facilities, but such a regime meets objectives shared by the United States and Russia (and, for that matter, by many other countries). Moreover, extensive data exchanges and verification measures have already been agreed for deployed strategic nuclear forces and other military systems.

Declarations of total stocks of weapons and fissile materials, with their locations, coupled with exchanges of operating records and inspections of material production sites, would reduce the large uncertainty in present estimates of these stocks. Fissile material production facilities and their operating

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records can be examined to confirm consistency with reported production figures, and stocks of fissile materials and weapons at declared sites can be confirmed through routine and occasional challenge inspections. The commitment of the Russian and U.S. governments to such declarations and the progressive opening of Russian society should make it less likely that a stockpile or production facility of any significant size could be hidden.

Dismantlement should also be monitored. The United States is dismantling its nuclear weapons at a rate of somewhat less than 2,000 per year, with a goal of increasing that rate to 2,000—the maximum rate permitted by available facilities; personnel; and environment, safety, and health (ES&H) considerations. The plutonium components ("pits") are being placed intact into containers and put in intermediate storage at the Pantex disassembly site near Amarillo, Texas. The HEU components are being shipped to the Y-12 plant at Oak Ridge, Tennessee, for storage and eventual use as naval or civilian reactor fuel. Russian spokesmen have declared that Russia is dismantling nuclear weapons at four sites, at a rate comparable to the U.S. rate, and is storing the materials at several existing sites.

Neither the United States nor Russia plans to monitor the other's dismantlement, although limited Ukrainian monitoring is reported to be in place in Russia. Means exist or could be developed to monitor dismantlement without undue interference or costs, while protecting sensitive information. As with other parts of the regime, some declassification would be necessary to permit effective monitoring. The basic approach would be a variant of the perimeter-portal monitoring system now in place to verify that missiles banned by the Intermediate-Range Nuclear Forces treaty are not being produced; war-heads entering and leaving the facility would be counted, and amounts of fissile material measured. Such monitoring could be applied without undue interference with necessary maintenance and modification of the remaining military stockpile.

A *cutoff of production of weapons materials* would require monitoring of enrichment and reprocessing facilities. Still greater confidence could be achieved if all fuel cycle facilities were monitored. These tasks could be carried out by bilateral or international monitors (or both), using means that have met international acceptance in nonproliferation verification. Continued production of HEU for naval reactors and tritium for nuclear stockpile maintenance would introduce some complications, but these could readily be addressed through careful design of the agreement and the monitoring system.

The United States is no longer producing plutonium or HEU for weapons. Russia has also ceased production of HEU for weapons, but is still operating plutonium production reactors and separating the resulting weapons-grade plutonium. The Russian government asserts that these reactors provide necessary heat and power to surrounding areas, and that the fuel must be reprocessed for safety reasons. The United States has begun discussions with Russia about assistance in converting these reactors so that separated weapons plutonium is not

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generated, or in providing alternate power sources, but these discussions remain embryonic.

Internationalizing the Regime

The security goals outlined above would be best served if the standards set by this regime for managing U.S. and Russian excess weapons and fissile materials were extended worldwide. In particular, new agreements should be pursued to:

1. create consistent, stringent international standards of accounting and security for fissile materials;
2. end all production of fissile materials for nuclear weapons, worldwide;
3. create an international system of declarations and inspections covering declared nuclear weapons arsenals, including reserves, and fissile material stocks (complementing the declarations and inspections already required of non-nuclear-weapon-state parties to the Non-Proliferation Treaty); and
4. create an international safeguarded storage regime under which all civilian fissile materials not in immediate use would be placed in agreed safeguarded storage sites, with agreed levels of physical security.

The IAEA secretariat and organizations in several countries are now working on concepts for such universal reporting and safeguarding of civilian fissile materials. These steps, and others that we recommend, would require increased resources for the IAEA, as well as organizational improvements. In some cases resources could be provided specifically for a new task. But the agency also urgently needs more resources overall.

INTERMEDIATE STORAGE

Present and Planned Arrangements

It will be necessary to provide secure intermediate storage of surplus weapons plutonium for decades, since long-term disposition will take years to start and possibly decades to complete. In both the United States and Russia, fissile materials from dismantled weapons are currently stored in the form of weapons components, some at the dismantlement site and some elsewhere. Neither country has yet decided how much will be held in reserve. No monitoring or transparency measures relating to storage of these fissile materials are yet in place, although the Clinton administration has announced that U.S. excess fissile materials will be placed under international safeguards, and Russia has expressed willingness to do the same. Russia and the United States also have tens of tons of weapons-grade plutonium not incorporated in weapons that are stored in various forms at several sites in their weapons complexes.

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In the United States, plutonium from weapons is being stored temporarily in simple "igloos" at Pantex, the dismantlement site. This arrangement provides high security and generally adequate standards of protection for environment, safety, and health. Given the stability of both the pits and the facilities at the site, there is no technical or economic reason why this arrangement could not be continued for a considerable time, but the public and the authorities in the area surrounding the site have been assured that interim storage there will not be extended beyond a decade. To meet that pledge, and to provide improved storage for plutonium in other forms now stored at several widely dispersed sites, the Department of Energy proposes to invest in a new, consolidated facility for long-term storage at a site to be selected. No full analysis of the advantages and disadvantages of this approach compared to upgrading existing storage facilities has been completed. We therefore do not offer a recommendation, though we recognize the safeguards and security advantages that a new consolidated facility might offer.

Less is known about Russian storage arrangements. Russia has requested, and the United States has agreed to provide, assistance in constructing a storage facility for excess fissile materials from weapons. We support construction of a facility designed to consolidate all these excess weapons materials, as this would facilitate security and international monitoring.

There is considerable debate concerning the optimum physical form in which to store plutonium. We recommend that, for the time being, plutonium continue to be stored in the form of intact weapons components. Decades of experience have demonstrated that pits are relatively safe and stable, and storage in this form would postpone the costs and ES&H issues of conversion to other forms. Although the design of pits is sensitive, international monitors could externally assay the amount of plutonium in a canister containing a pit without, in most cases, revealing sensitive design information. Intact pits can more easily be reused for weapons by the state that produced them than plutonium in other forms, but they probably do not pose substantially greater proliferation risks than storage as deformed pits or metal ingots. Deformation of pits and perhaps other steps to reduce the rearmament risk should be given serious consideration, and should be undertaken if they can be accomplished at relatively low cost and ES&H risk.

One cannot be confident, however, that plutonium in pits can be stored without degradation for more than a few decades. When a definite decision regarding long-term disposition has been made, the pits should be converted into the forms required for that disposition option, under agreed safeguards and security.

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A New Storage Regime

The following measures constitute a regime for intermediate storage of surplus fissile materials that serves the objectives noted earlier with minimum disruption to the process of dismantlement and storage:

1. *Commitment to Non-Weapons Use*. The United States and Russia should commit a large fraction of the fissile materials from dismantled weapons to non-weapons use. They should agree on the specific amounts.
2. *Safeguarded Storage and Disposition*. The preceding commitment should be verified by monitoring of the present and future sites where fissile materials are stored, and continued monitoring of the material after it leaves these sites for long-term disposition.
3. *IAEA Involvement*. Although such monitoring might begin bilaterally, the IAEA should be brought into the process expeditiously, in an expansion and strengthening of its nonproliferation role. The IAEA would monitor the amount of material in the storage site and safeguard any material removed from the site to ensure its use for peaceful purposes. Such safeguards would be an extension of the existing safeguards system. Bilateral monitoring would probably continue as well.

Financial or other incentives could be provided to Russia for putting the material into storage. Management, control, or outright ownership of the stores and the material in them might be transferred to other parties, such as an international consortium formed for that purpose. The material might even be physically relocated to some other country, possibly in return for cash, as in the case of the HEU deal. Such incentives would not obviate the need for, and are secondary to, prompt agreement on a storage regime along the lines recommended here.

LONG-TERM DISPOSITION

Categories, Criteria, and Standards

The technical options for long-term disposition of excess weapons plutonium can be divided into three categories:

- *indefinite storage*, in which the storage arrangements outlined in the previous section would be extended indefinitely;
- *minimized accessibility*, in which physical, chemical, or radiological barriers would be created to reduce the plutonium's accessibility for use in weapons (either by potential proliferators or by the state from whose weapons it came), for example, by irradiating the plutonium in reactors or mixing it with high-level wastes; and
- *elimination*, in which the plutonium would be made essentially completely inaccessible, for example, by burning it in reactors so completely that only a

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few grams would remain in a truckload of spent fuel, or by launching it into deep space.

In both the "minimized accessibility" and the "elimination" categories, some of the options *use* the plutonium to generate electricity, while others *dispose* of the plutonium without using its energy content. Both classes of options would involve net economic costs. The electricity generation options would produce revenues, but the costs of using plutonium to produce this electricity would be higher than the costs of generating it using enriched uranium. The current Russian government nonetheless sees weapons plutonium as a valuable asset and therefore strongly prefers options that use the plutonium.

Risks of Storage. Although intermediate storage is an inevitable step preceding all disposition options, it should not be extended longer than necessary. Maintaining this material in a readily weapons-usable form over the long term would send negative political signals for nonproliferation and arms reduction, and the security offered by indefinite storage against the risks of breakout and theft is entirely dependent on the durability of the political arrangements. Indeed, one of the key criteria by which disposition options should be judged is the speed with which they can be accomplished, and thus how rapidly they curtail these risks of storage.

Risks of Handling—The "Stored Weapons Standard." Although options in the "minimized accessibility" and "elimination" classes decrease the long-term accessibility of the material for weapons use, they could increase the short-term risks of theft or diversion because of the required processing and transport steps. In order to ensure that the overall process reduces net security risks, an agreed and stringent standard of security and accounting must be maintained throughout the disposition process, approximating as closely as practicable the security and accounting applied to intact nuclear weapons. We call this the "stored weapons standard." These risks of handling are a second key criterion for judging disposition options.

Risks of Recovery—The "Spent Fuel Standard." A third key security criterion for judging disposition options is the risk of recovery of the plutonium after disposition. We believe that options for the long-term disposition of weapons plutonium should seek to meet a "spent fuel standard"—that is, to make this plutonium roughly as inaccessible for weapons use as the much larger and growing quantity of plutonium that exists in spent fuel from commercial reactors. Options that left the plutonium more accessible than these existing stocks would mean that this material would continue to pose a unique safeguards problem indefinitely. Conversely, the costs, complexities, risks, and delays of going beyond the spent fuel standard to eliminate the excess weapons plutonium completely, or nearly so, would not be justified unless the same approach were to be taken with the global stock of civilian plutonium. Over the long term, however, steps beyond the spent fuel standard will be necessary—for both the weapons plutonium and the larger civilian stock—as described below.

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In addition, policymakers will have to take into account the political impact that the use of excess weapons plutonium in reactors, or the disposal of that plutonium, would have on nuclear fuel cycle debates abroad. Whatever choice it makes, the United States will have to explain how that choice fits into the broader context of its nonproliferation and fuel cycle policies.

The Preferred Approaches

The best means of plutonium disposition may well differ in the United States and Russia, given that the two countries have different economies, reactor and waste infrastructures, and plutonium fuel policies, and given that very different safeguards and security risks currently pertain.

As noted above, there are two options that hold especially strong promise of being able to meet the criteria just outlined: the use of plutonium as fuel in existing or modified reactors without reprocessing, and vitrification together with high-level wastes. A third option, burial in deep boreholes, might prove on further study to be on a par with the first two. We now describe each of these options in turn.

The Spent Fuel Option

Excess weapons plutonium could be used as fuel in reactors, transforming it into intensely radioactive spent fuel similar in most respects to the spent fuel produced in commercial reactors today. This use could probably begin within approximately 10 years (paced by obtaining the necessary fuel fabrication capability and the needed approvals and licenses) and be completed within 20 to 40 years thereafter (paced by the number of reactors used, the fraction of the reactor core using plutonium fuel, the percentage of plutonium that this fuel contains, and the amount of time that the fuel remains in the reactor). Examples include:

- *U.S. Light-Water Reactors.* The predominant commercial reactors in the world today are light-water reactors (LWRs). Without major modifications, typical LWRs could burn a fuel consisting of mixed oxides of plutonium and uranium (MOX) in one-third of their reactor cores. Four existing LWRs in the United States (three operational at Palo Verde in Arizona, and one 75 percent complete in Washington State) were designed to use MOX in 100 percent of their reactor cores; a single such reactor, using fuel containing somewhat more plutonium than would be used if energy production alone were the aim, could transform 50 tons of weapons plutonium into spent fuel in 30 years. Alternatively, other operating or partly completed reactors could also be modified to use full MOX cores, or a new full-MOX reactor might be built on a government site, with costs partly offset by later sales of electricity.

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Although the United States has no operating MOX fuel fabrication capability, there is an unfinished facility at the Hanford site that could be completed and modified for this purpose; alternatively, a new MOX facility could be built in roughly a decade, at significantly higher cost.

This option is technically demonstrated, as LWRs in several countries are burning MOX fuels today. Environmental, health, and safety risks can be minimized with the application of money and good management, although some of the specifics of how best to do so require further study. Use of MOX fuels, however, would be controversial in the United States, where such fuels are not now used, and gaining licenses and public approval could raise difficulties. The subsidy required to transform 50 tons of plutonium into spent fuel in this way (compared to the cost of producing the same electricity by the means with which it would otherwise be produced) would probably fall in the range from a few hundred million to a few billion dollars, depending on assumptions and on the specific approach chosen.

- *Russian Light-Water Reactors*. Similarly, Russian plutonium could be used as MOX in Russian VVER-1000 reactors (the only existing reactors in Russia likely to be safe enough and long-lived enough for this mission). VVER-1000s that are not yet operational, but that the Russian government plans to complete for electricity production, could be modified to handle full MOX cores, or such modifications could be incorporated in operating reactors during the shutdowns for safety improvements that are now planned. Because of the current political and social upheaval in Russia, safeguards and security risks would be substantial. The current Russian government's preference for storing plutonium until it can be used in the next generation of Russian liquid-metal fast reactors is not attractive because of the indefinite time before disposition could begin, the security liabilities of prolonged storage, and the high cost of these reactors.
- *CANDUs*. Existing Canadian deuterium-uranium (CANDU) reactors are a technically attractive possibility for this mission, because the reactor design allows them inherently to handle full-MOX cores, with less change from the usual physics of the reactor than in the case of LWRs. The cost of this option is difficult to estimate, as no one has yet attempted to fabricate MOX fuel for CANDU reactors on any significant scale. We do not know whether the opportunity for Canada to participate in an important disarmament process, combined with possible U.S. subsidies for the project, would be attractive enough to cause that country to reverse its long-standing policy against the use of fuels other than natural uranium in its power reactors.
- *Substitution for Civilian Plutonium*. Utilities in Europe and Japan currently plan to use more than 100 tons of reactor-grade plutonium in MOX fuels over the next decade. If excess weapons plutonium from Russia or the United States were substituted for this material—with an associated delay in separation

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of plutonium from civilian spent fuel, so that additional excess stocks of civilian plutonium did not build up as a result—disposition of 50 or even 100 tons of plutonium could be accomplished relatively rapidly (since the facilities required are already built and licensed, or scheduled to be) and with comparatively small *net additional* safeguards risks (since after the initial transport, all the facilities handling plutonium would have done so in any case). However, the agreements required to implement this option would be complex and probably difficult to reach. Substantial changes in a variety of existing contracts and programs would have to be made, and transport of weapons plutonium to these countries would be controversial.

- *New Reactors for the Plutonium Mission*. Given the high costs and long times required for the construction of new reactors, building such reactors for the mission of transforming weapons plutonium into spent fuel would be justifiable only if problems of licensing and public acceptance made currently operating or partly completed reactors unavailable (and only, of course, if the reactor-MOX option were deemed preferable to the vitrification and deep-borehole approaches). If that proves to be the case, the new reactors should be built on a government-owned site and should be of sufficiently well-proven design so as not to create additional technical and licensing uncertainties. Reactors we have examined of more advanced design do not offer sufficient advantages for this mission to offset the extra costs and delays that their use would entail. In particular, the use of advanced reactors and fuels to achieve high plutonium consumption without reprocessing is not worthwhile, because the consumption fractions that can be achieved—between 50 and 80 percent—are not sufficient to greatly alter the security risks posed by the material remaining in the spent fuel. Development of advanced reactors and fuel types is of interest for the future of nuclear electricity generation, including the minimization of safety and security risks, but the timing and scope of such development need not and should not be governed by the current weapons plutonium problem.

The Vitrification Option

An alternative means of creating similar radioactive and chemical barriers to weapons use of this material would be to mix it with radioactive high-level waste (HLW) left from the separation of plutonium from weapons and other defense activities. Under current plans, HLW will be mixed with molten glass (vitrified) to produce large glass logs. These logs, like spent reactor fuel, will be stored for an interim period and then placed in a geologic repository. The logs would pose radiological barriers to handling and processing similar to those of spent LWR fuel a few decades old. Incorporating plutonium into these logs appears feasible, although technical questions remain. These technical issues are more substantial than those facing the MOX options, but licensing and public approval appear easier to obtain in the vitrification case, at least in the

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United States. Vitrification raises fewer security risks in handling than the MOX option, because the process of mixing plutonium with HLW would be easier to safeguard than the more complex process of fabricating MOX. This might be of particular importance in the current Russian context. Russian vitrification efforts have so far focused on a phosphate glass that is less appropriate for this mission than the borosilicate glass used in the United States and elsewhere because it is less durable and offers less protection against the possibility of an unplanned nuclear chain reaction once plutonium is embedded in it. New technologies for comparatively small melters could be transferred to Russia for this purpose. So far, however, the Russian officials responsible for these issues have rejected disposal options such as vitrification.

The Deep-Borehole Option

Disposal in deep boreholes has been examined in several countries as an approach to spent fuel and HLW management, and is still being examined in Sweden. Because of the very great depth of the holes, there are good reasons to believe that the materials emplaced would remain isolated from the environment for periods comparable to or possibly longer than those expected for the geologic repository case, but significant uncertainties must be resolved. Plutonium in such boreholes would be extremely inaccessible to potential proliferators, but would be recoverable by the state in control of the borehole site. The method would be relatively inexpensive to implement, but developing sufficient confidence to permit licensing could be costly and time-consuming; the United States has expended decades and billions of dollars in preparation for such licensing in the case of geological repositories for spent fuel and HLW.

All three of these options have the potential to be satisfactory next steps beyond interim storage in the disposition of excess weapons plutonium. None of them, however, could be confidently selected until currently open questions, described in Chapter 6 of this report, are answered.

Other Approaches

A variety of other reactors have been proposed for this mission, such as high-temperature gas-cooled reactors, fast-neutron reactors, or various existing research or plutonium production reactors. Existing reactors other than the LWRs and CANDUs described above should be rejected on grounds of the uncertain availability and safety of those reactors with sufficient capacity. The advanced reactors, as noted above, are not competitive for this mission because of the cost and delay of their development, licensing, and construction.

A variety of exotic disposal options have also been proposed, including sub-seabed disposal, detonation in underground nuclear explosions, launching into deep space, and dilution in the ocean, among others. This report rejects all

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of these on grounds of retrievability, cost, delay, environmental concerns, or conflict with existing policies and international agreements.

Beyond the Spent Fuel Standard

Long-term steps will be needed to reduce the proliferation risks posed by the entire global stock of plutonium, particularly as the radioactivity of spent fuel decays. Options for reducing these risks could include placement of spent fuel in geologic repositories, or pursuit of fission options that would burn existing plutonium stocks nearly completely. A variety of reprocessing-oriented reactor options have been proposed for this mission, ranging from the use of standard LWRs to challenging concepts such as accelerator-based conversion. The costs of these approaches would be in the tens or hundreds of billions of dollars, and the time scales would be many decades or centuries, depending on the choice of options. These technologies can only be realistically considered in the broader context of managing the future of nuclear power to provide energy while minimizing the risk of nuclear proliferation, an important task that is beyond the scope of this committee. To further refine these concepts, research on fission options for near-total elimination of plutonium should continue at the conceptual level.

Although all the plausible disposition options will take many years to implement, it is important to begin now to build consensus on a road map for decision. Such a road map would provide guidelines for the necessary national and international debate to come, focus further efforts on those options most likely to minimize future risks, and provide plausible end points for the process that the near-term steps will set in motion. Research and development should be undertaken immediately to resolve the outstanding uncertainties facing each of the options.

THE INSTITUTIONAL FRAMEWORK

The institutional and political issues involved in managing weapons dismantlement, intermediate storage of fissile materials, and long-term disposition may be more complex and difficult to resolve than the technical ones. Because disposition options will require decades to carry out, it is critical that decisions throughout be made in a way that can muster a sustainable consensus. The entire process must be carefully managed to provide adequate safeguards, security, and transparency; to obtain public and institutional approval, including licenses; and to allow adequate participation in the decision making by all affected parties, including the U.S. and Russian publics and the international community. Adequate information must be made available to give substance to the public's participation.

These issues cover a broad institutional and technical spectrum. Establishing fully developed arrangements for managing these tasks will require an unusually

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demanding integration of policy under conditions of dispersed authority and intense political sensitivity. In the United States, jurisdiction over fissile material and fabricated weapons is divided between the Department of Energy (DOE) and the Department of Defense (DOD) in different phases of the deployment cycle. Each department has many subordinate divisions involved. Related diplomacy is handled by the State Department and the Arms Control and Disarmament Agency, with input from DOE and DOD. Numerous other agencies perform supporting functions. The relevant installations are authorized and financed by Congress, regulated by independent agencies and commissions, constrained by state laws, and increasingly affected by public opinion in their surrounding communities. Policy debates too often focus on specific options, such as particular reactor types, rather than the comprehensive view required to make choices for this complex problem. The consequences of this fragmentation are illustrated in a related area by the fact that technical assessment of the U.S. high-level waste repository at Yucca Mountain is incomplete after two decades of work and billions of dollars of expenditure, and final licensing is not projected for another two decades. These challenges to comprehensive policymaking are at least as great in Russia, where they must be surmounted in the midst of continuing political and economic upheaval.

None of the governments involved have previously faced the problem of handling excess plutonium in the quantities now contemplated, and none appear to have developed policies and procedures likely to be adequate to the task. Yet decisions are urgent, since without new approaches even the near-term tasks of dismantlement and storage are not likely to meet all of the required security criteria.

In these areas, the United States bears a special burden of policy leadership. If demanding technical assessments are to be completed, if consensus is to be forged, and if implementation is to be accomplished in reasonable time, major advances in the formulation and integration of policy and in institutional coordination will be needed. The president should establish a more systematic process of interagency coordination to deal with the areas addressed in this report, with sustained top-level leadership. The new interagency examination of plutonium disposition options envisioned in President Clinton's September 27, 1993, nonproliferation initiative is a first step in that direction, but much more remains to be done.

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Introduction: Task and Context

THE TASK

With the end of the Cold War, the world is faced for the first time with the need to manage the dismantlement of vast numbers of "excess" nuclear weapons and the disposition of the fissile materials they contain. If recently agreed reductions are fully implemented, tens of thousands of nuclear weapons, containing a hundred tons or more of plutonium and many hundreds of tons[1] of highly enriched uranium (HEU), will no longer be needed for military purposes. These two materials are the essential ingredients of nuclear weapons, and limits on access to them are the primary technical barrier to acquiring nuclear weapons capability in the world today. Several kilograms of plutonium, or several times that amount of HEU, are sufficient to make a nuclear weapon.[2] These materials will continue to pose a potential threat to humanity for as long as they exist.

The task of managing this reversal of the arms competition is complicated by the breakup of the Soviet Union and the continuing political and economic

[1] Throughout this report metric tons (MT) are used as the measure of the amounts of plutonium and HEU; all references to tons are to metric tons. One metric ton is 2,205 pounds, roughly 10 percent more than an English ton.

[2] For purposes of this study, 4 kilograms of plutonium per weapon will be used as a planning figure. The minimum quantities of plutonium or HEU needed to make a weapon are not well defined, since they depend on the design. Actual quantities used in U.S. weapons are classified.

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and some typographic errors may have been accidentally inserted. Please use the print version of this publication as th

crises in the former Soviet states. There are substantial risks that more than one nuclear state could arise from the former Soviet Union, that the recently agreed arms reductions could stall, and that control over nuclear weapons or fissile materials could erode, increasing the danger that they would fall into the hands of unauthorized parties. Urgent actions are required to secure and account for these weapons and materials.

The task is pressing, but the solutions will be complex, expensive, and long-term. The process can be divided into three distinct but overlapping phases: dismantlement of nuclear weapons, intermediate storage of fissile materials, and long-term disposition of those materials.[3] Figure 1-1 outlines the policy choices at each stage; Figure 1-2 gives an idea of the time scales involved. For each of these stages, critical policy choices must be made, with wide-ranging implications for both arms reduction and nonproliferation. Indeed, without new approaches to managing the reductions process, it is unlikely that long-term U.S. arms reduction and nonproliferation objectives can be achieved.

Dismantlement of weapons and storage of the resulting fissile materials are already under way. Final disposition of the materials will take far longer to accomplish. The HEU from nuclear weapons can be blended to make a reactor fuel that poses little proliferation risk and can return a substantial economic benefit, but disposition of weapons plutonium is far more problematic; hence, plutonium is the primary focus of this report. There are no easy answers to the plutonium problem. Policymakers will have to choose from a variety of imperfect options, requiring inherently judgmental trade-offs among different categories of risks.

It will be more than a decade before any of the plausible options for long-term disposition of weapons plutonium makes a substantial dent in the likely excess stockpile. Most of the options would require 20 to 40 years to accomplish the task.[4] Although use of HEU as reactor fuel could return a profit large enough to pay for most of the tasks just described, all of the options for disposition of plutonium are likely to involve net economic costs, not net benefits, because in the current market plutonium is a more expensive reactor fuel than widely available uranium (see "The Value of Plutonium," p. 24). Thus plutonium disposition is fundamentally a problem of security, far more than one of efficient utilization of assets. Exploiting the energy value of plutonium should not be a central criterion for decision, both because plutonium cannot compete economically with uranium in the current market, and because whatever economic value this plutonium might represent now or in the future is small by

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[3] The processes of retiring the nuclear weapons from active duty, disabling them, bringing them to dismantlement sites (if necessary, from foreign deployment), and retiring or dismantling the launchers involved are also critical parts of the arms reduction process, but are beyond the scope of this report.

[4] Even in the simpler case of HEU, which the United States plans to purchase from the states of the former Soviet Union for use as nuclear fuel, the planned transfer—still being negotiated—would extend over 20 years.

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Management and Disposition of Excess Weapons Plutonium

comparison to the security stakes. The cost of management and disposition of weapons plutonium must be seen as an investment in security, just as the cost of its production was once viewed.

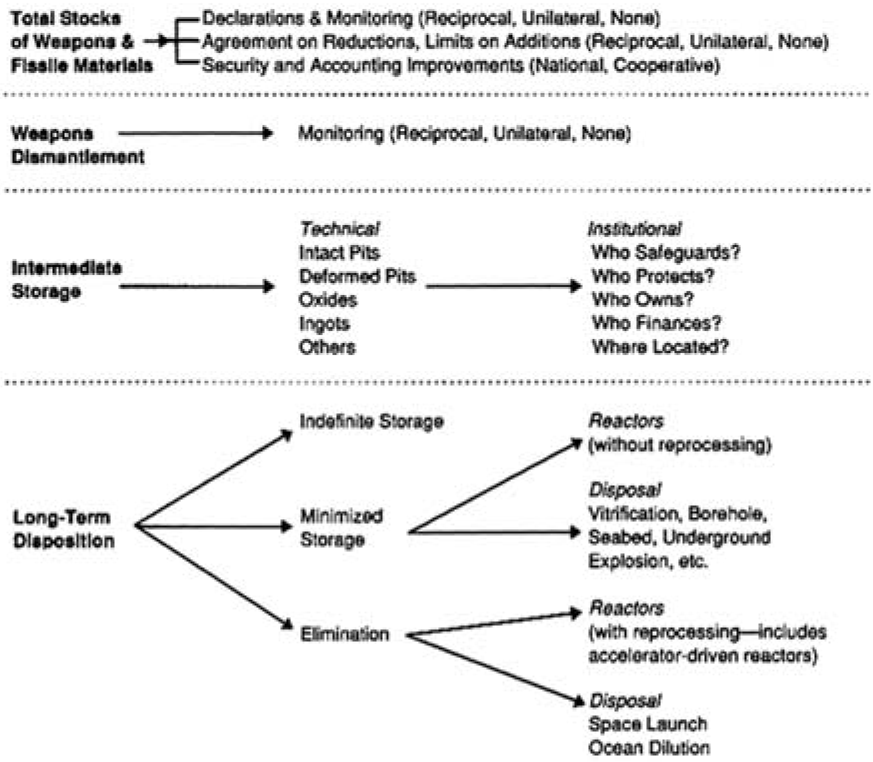

FIGURE 1-1 Phases of plutonium management

All of the options for long-term plutonium disposition will require many years to complete. Thus, storing this material is the only available near-term option. The United States and Russia must quickly develop appropriate technical and institutional arrangements for dismantlement and storage, following through on the discussions already under way. Judgments about the most desirable immediate approaches for these tasks must necessarily be based on conditions that exist or can be readily foreseen today. At the same time, these storage arrangements must be designed to endure for decades.

Planning for long-term disposition of plutonium will inevitably involve more uncertain extrapolations of risks—although because of the longer time involved, it will also be easier to make corrections in planning over time. Thus, this report does not provide a single definitive answer for the disposition phase

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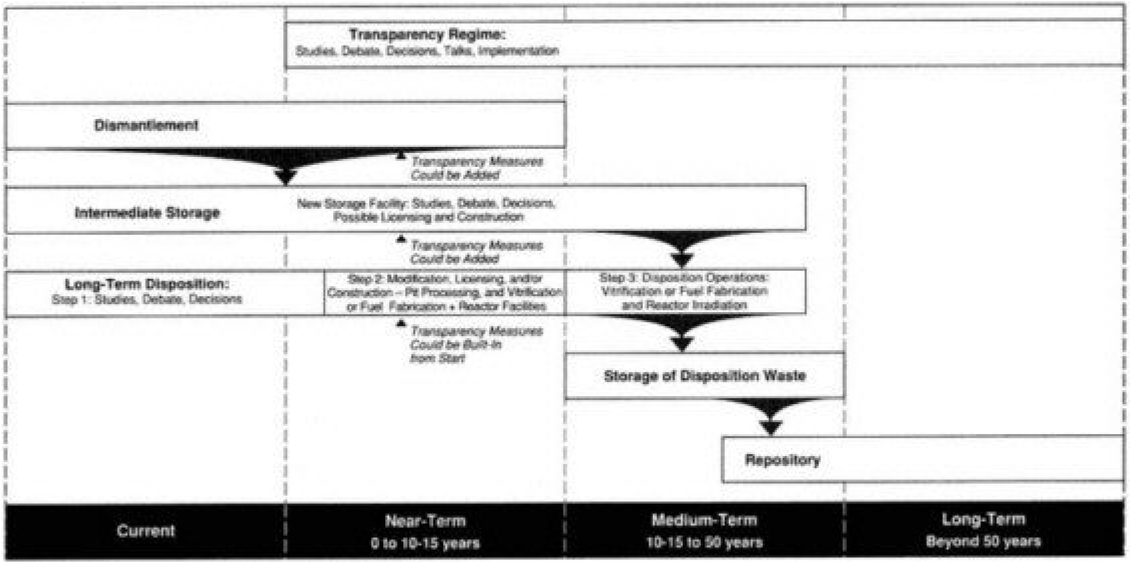

FIGURE 1-2 Timeline for plutonium management and disposition
The figure shows that the transparency regime could be decided on and implemented in the near term, and continue indefinitely thereafter. Dismantlement is ongoing and will continue through the near term. Intermediate storage is ongoing and will continue through the near term and most of the medium term, possibly with a new storage facility being built in the near term. Step 1 of long-term disposition will continue into the first years of the near term; Step 2 can be accomplished during the near term; and Step 3 will take most of the medium term. Step 3 will result in disposition waste, which will be stored until a geologic repository is available.

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of the plutonium problem. Instead it offers a road map, whose objective is to provide guidelines for the necessary national debate to come and to focus further efforts on those options most likely to minimize future risks. Such a road map can help avoid wasting resources on options with little promise and can provide plausible end points for the process that the near-term steps will set in motion. Developing a broad consensus on such a road map deserves high priority.

OBJECTIVES

The primary goal in choosing options for management and disposition of excess nuclear weapons and fissile materials should be to minimize the risks to national and international security posed by the existence of this material. This security goal can be divided into three main objectives:

1. to minimize the risk that weapons or fissile materials could be obtained by unauthorized parties;
2. to minimize the risk that weapons or fissile materials could be reintroduced into the arsenals from which they came, halting or reversing the arms reduction process; and
3. to strengthen the national and international control mechanisms and incentives designed to ensure continued arms reductions and prevent the spread of nuclear weapons.

In addition to these security objectives, all options must protect worker health and the environment, and be acceptable to the public. Timing, which plays an important part in whether the security criteria can be met, and consistency with other policies and objectives will also be important criteria for choice.[5]

Cost will inevitably also be an important consideration. The committee notes, however, that the expenditures implied by all its recommendations combined would total at most several billion dollars, spread over a period of a decade or decades. Since the primary objective is the reduction of major security risks, these expenditures should be considered in the context of the far larger sums being expended every year to provide national and international security. Thus, cost should not be the primary criterion in choosing among competing options.

The most immediate threat to all three of the security objectives is only partly related to the management and disposition of excess weapons and fissile materials. This is the possibility that more than one nuclear state may emerge from the breakup of the Soviet Union. Ukraine is the greatest apparent risk.

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[5] For more detail on the criteria for choice, see Chapter 3; for more detail on how a regime for management and limitation of weapons and fissile materials could affect the security objectives, see Chapter 4.

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THE VALUE OF PLUTONIUM

As a result of reductions in the nuclear arsenal, large quantities of plutonium are no longer needed for military purposes and thus are not an asset in military terms. Is plutonium an *economic* asset, given its substantial energy content, and the large sunk costs of its production? The current nuclear fuels market is dominated by the fuel needs of light-water reactors (LWRs). Plutonium oxide could in principle be mixed with depleted or natural uranium oxide to make a mixed-oxide (MOX) fuel that could be used in LWRs, instead of the low-enriched uranium (LEU) fuel they generally use (see Chapter 6). Whether such a substitution is economically competitive in the case of weapons plutonium depends on the costs of several commodities, including uranium, enrichment, LEU fuel fabrication, conversion of plutonium pits to oxide, and MOX fuel fabrication.

Estimates of the current and future prices for all of these vary considerably. Plutonium's radiological toxicity requires special handling, and its usability as a weapons material imposes stringent security and safeguards requirements, making the cost of MOX fuel fabrication several times greater than the cost of LEU fuel fabrication. No operational MOX fabrication plants exist in either the United States or Russia, so the capital cost of building such a plant or modifying existing facilities for this purpose must be included in the cost of MOX fabrication. The main question is whether "free" plutonium, whose use involved both this higher fabrication cost and the cost of converting plutonium metal to oxide, would be cheaper to use as fuel than uranium that had to be mined and enriched. After examining the various estimates of the prices involved, the committee has concluded that a realistic estimate is that the cost of MOX fuel starting from plutonium metal provided free of charge (if fabricated in a nearly completed facility that already exists at Hanford, at a rate of about 50 tons a year) would be $500 per kilogram of heavy metal more than the cost of comparable LEU fuel, with an uncertainty of plus or minus $350. The cost differential would be higher if a new facility had to be built to fabricate the MOX fuel, and higher still if the facility operated with a lower throughput.[1] Only by combining very pessimistic assumptions about LEU costs with very optimistic assumptions concerning MOX prices could one reach the conclusion that MOX made from free plutonium could be economically competitive.

Since each kilogram of MOX fuel would include only 30 to 70 grams of weapons plutonium, the excess cost for each kilogram of plutonium—rather than each kilogram of fuel—would be much larger. Assuming, as a reference, a loading of just under 5 percent plutonium in the fuel, the economic penalty for using MOX instead of LEU would amount to $10,000 per kilogram

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Management and Disposition of Excess Weapons Plutonium

of plutonium (plus or minus $7,000), using the least expensive of the MOX fabrication options identified. The cost of processing 50 tons of plutonium in this way would then be $500 million (plus or minus $350 million). This figure would be substantially higher if the more expensive fabrication approaches were used. These estimates relate only to the excess fuel costs, and do not account for any necessary expenditures for modifying existing reactors or building new ones to burn plutonium, licensing the relevant facilities, any increase in spent fuel disposal costs resulting from plutonium use, and the like.

For reactor types that use more enriched fuels, such as liquid-metal reactors or high-temperature gas-cooled reactors, fuel made from free plutonium would be competitive because of the higher costs of uranium purchases and enrichment when reactors of these types use uranium fuels. These reactor types themselves, however, are not currently economically competitive with other sources of power, and the availability of free plutonium as fuel would not make them so. Storage of large stocks of weapons plutonium until such reactors become competitive is not attractive for security reasons. Moreover, with the prices paid for plutonium storage in the commercial market, the storage cost would quickly outweigh the potential value of the plutonium.

Oil shale provides a useful comparison. Like plutonium, such shales contain substantial energy value. But like plutonium, that energy cannot be used without first making substantial investments, and the alternative fuels available—crude oil, in the case of oil shale—are significantly cheaper in the current market. Some day, as oil becomes scarce, oil shale will probably become valuable; similarly, as uranium supplies run out, plutonium is likely to become valuable. But neither of these commodities has economic value today. The difference, of course, is that large stocks of excess plutonium, unlike oil shale, pose major security risks.

In short, in strictly economic terms, excess weapons plutonium is more a liability than an asset. No matter what approach is taken to long-term disposition, the process is likely to involve a net economic cost, rather than a net benefit. An important question addressed in this study, therefore, is the comparison of the net additional cost required to use this plutonium in reactors, compared to the cost of disposal options that would not make use of its energy content.

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[1] These estimates are explained in detail in *Management and Dispositionof Excess Weapons Plutonium: Report of the Panel on Reactor-RelatedOptions* (Washington, D.C.: National Academy Press, 1994). The uncertainty ranges represent judgmental 70 percent confidence intervals, corresponding to roughly one standard deviation of a random variable—that is, a judgment that there is a 15 percent chance that the cost would be higher, and a 15 percent chance that it would be lower.

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President Leonid Kravchuk, in the Lisbon Protocol of 1992 and an accompanying letter, established a formal international commitment to denuclearization. But that commitment remains the subject of intense debate in Ukraine, bringing the implementation of current strategic arms reduction agreements into question. In November 1993, the Ukrainian Rada voted to ratify the first Strategic Arms Reduction Treaty (START I) without accepting the denuclearization commitment, explicitly exempting more than half of the missiles on Ukrainian soil from elimination. Efforts to resolve this issue are continuing, and Kravchuk has said he will resubmit the agreement to a new parliament in 1994. If Ukraine actually reversed its commitment and attempted to acquire an independently controlled nuclear arsenal, the entire framework of nuclear arms reduction and nonproliferation would be severely, perhaps fatally, damaged. Security concerns may well be the driving factors in Ukraine's ultimate decision, but that decision could be affected by measures to ensure that weapons and fissile materials transferred to Russia will not be reused for military purposes, and to provide compensation for these materials.

Beyond that immediate issue, decisions about excess nuclear weapons and fissile materials are likely to have far-reaching consequences for each of the three security goals just described:

The Risk of Theft.[6] Restricting access to fissile material is the principal technical barrier to proliferation in today's world, far more so than access to the information and technologies needed to build a weapon once the fissile material has been acquired. This makes the task of securing weapons and fissile materials critical.[7] The risk that nuclear weapons or fissile materials could fall into unauthorized hands—whether through theft, sale, or other means—can be reduced by steps taken singly and jointly to keep strict accounting of these materials; to improve their security; to strengthen the organizations responsible for their management; and to dismantle weapons and transfer the resulting materials into secure, monitored storage and ultimately to civilian use or disposal. In addition, a well-designed regime to carry out such steps could provide a new and compelling mission for the organizations once charged with producing nuclear weapons, reducing the risks that control could erode.

The Risk of Reversal. Even after the START I and START II agreements enter into force and the reductions they call for are implemented, as long as the retired warheads and the material they contain remain in usable form, the risk

[6] Although in many contexts the term "diversion" is used to mean any case in which an unauthorized party obtains a particular item, in the parlance generally employed in international nonproliferation efforts, particularly by the International Atomic Energy Agency (IAEA), a distinction is made between "diversion" and "theft." *Diversion*refers to the state that owns material under safeguards removing it for weapons purposes, whereas *theft* refers to acquisition of these materials by other unauthorized parties. This report follows that convention.

[7] The current concern about North Korea's possible possession of several kilograms of separated plutonium highlights the importance of tight controls over these materials.

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will remain that one of the parties may decide to rebuild its nuclear arsenal in contravention of its agreements and pledges. The retired weapons could be used directly, or the materials from them could be used to fabricate new warheads. This risk could be reduced by agreements designed to make such a rearmament program more difficult, time-consuming, costly, and easily detected. These could include agreements to verifiably dismantle the weapons, to create barriers to reusing the resulting fissile material for new weapons, and to improve transparency for the stocks of nuclear weapons and fissile materials.

Strengthening Arms Reduction and Nonproliferation. The current arms reduction regime would be politically strengthened by appropriate measures to increase transparency and cooperation in managing excess weapons and fissile materials. Such measures would help convince doubters worldwide, including those in the United States, Russia, and Ukraine, that the arms reduction regime serves the interests of all parties. Credible controls and transparency would also provide a critical foundation for pursuing deeper reductions, and for convincing other nuclear powers to limit and reduce their nuclear arsenals as well.

Policy choices in this area will also have a major impact on the future of efforts to stem the spread of nuclear weapons. The foundation of these efforts is the nuclear Non-Proliferation Treaty (NPT), which is up for extension in 1995. A critical question at the extension conference will be whether the nuclear powers are fulfilling their disarmament obligations under Article VI of the NPT.[8] The current effort to negotiate a comprehensive test ban (CTB), along with recent arms reduction agreements and pledges, should allow the nuclear powers to make a strong case—if these efforts are moving forward at the time of the conference and are not derailed. Agreements for secure, safeguarded management and disposition of fissile materials from surplus nuclear weapons would make the case even stronger. Moreover, acceptance by the major nuclear powers of safeguards and constraints on substantial portions of their nuclear programs would help to reduce the inherently discriminatory nature of the nonproliferation regime. These steps, while probably not dissuading all nations that might be attempting to acquire nuclear weapons, would help build global political support for indefinite extension of the NPT and strengthening the regime, which are major U.S. policy goals. In addition, steps to improve control and management of fissile materials from dismantled weapons could provide an opportunity for taking similar steps with other fissile materials worldwide.

To achieve these objectives, the challenge of arms reduction should be managed in a way that offers political support to both the arms reduction and the nonproliferation regimes. In particular, approaches to these and other issues involving the states of the former Soviet Union must avoid strictures so onerous or one-sided that they provide new ammunition to domestic political opponents.

[8] Article VI requires all parties to the treaty to "pursue negotiations in good faith on effective measures relating to cessation of the nuclear arms race at an early date and to nuclear disarmament, and on a treaty on general and complete disarmament under strict and effective international control."

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The future of civilian nuclear power depends on economic, political, and technical factors outside the scope of this study. In some countries, nuclear power programs already include the use of plutonium in the fuel loaded into reactors. But the amount of weapons plutonium likely to be surplus is small on the scale of global nuclear power use—amounting to the equivalent of only a few months of fuel for existing reactors—and this stock of weapons plutonium is not essential to the future of any civilian nuclear development programs. There is thus no reason that disposition of this weapons plutonium should drive decisions on the broader questions surrounding the future of nuclear power.

THE CONTEXT: WORLD STOCKS OF FISSILE MATERIALS

The plutonium and HEU resulting from arms reductions are only part of the world's stocks of these materials, which include:

1. military plutonium and HEU in operational nuclear weapons and their logistics pipeline;
2. military plutonium and HEU held in reserve for military purposes, in assembled weapons or in other forms;
3. military plutonium and HEU withdrawn from dismantled weapons and considered excess;
4. separated plutonium and HEU in storage in preparation for use in military or civilian reactors;
5. plutonium and HEU currently in reactors;
6. irradiated plutonium and HEU in spent fuel from reactors; and
7. military and civilian plutonium and HEU outside the categories above, including excess stocks, scrap, residues, and the like.

The problem of management and disposition of excess weapons plutonium (category 3) is the focus of this report, but policy for it must take into account the large stocks of plutonium and HEU in these other categories since, with varying degrees of difficulty, they can all be used in nuclear weapons (see Figure 1-3).

Although all but a small fraction of the world's HEU is in military use, civilian stocks of plutonium are several times larger than the military stocks and are growing much faster, by some 60 to 70 tons each year. Most of these civilian stocks, however, are in the form of radioactive spent fuel from the world's power reactors. The difficulty of extracting this plutonium declines substantially as the radioactivity of the fuel decays over the decades after it leaves the reactor. Some plutonium is being separated from spent fuel for use as reactor fuel. Separation has outpaced use of this plutonium; roughly 80 to 90 tons of excess separated civilian plutonium is in store around the world today, representing more than half of all the civilian plutonium that has ever been

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separated from spent fuel. That figure is expected to grow, as more civilian plutonium continues to be separated each year than is used in reactor fuel.[9]

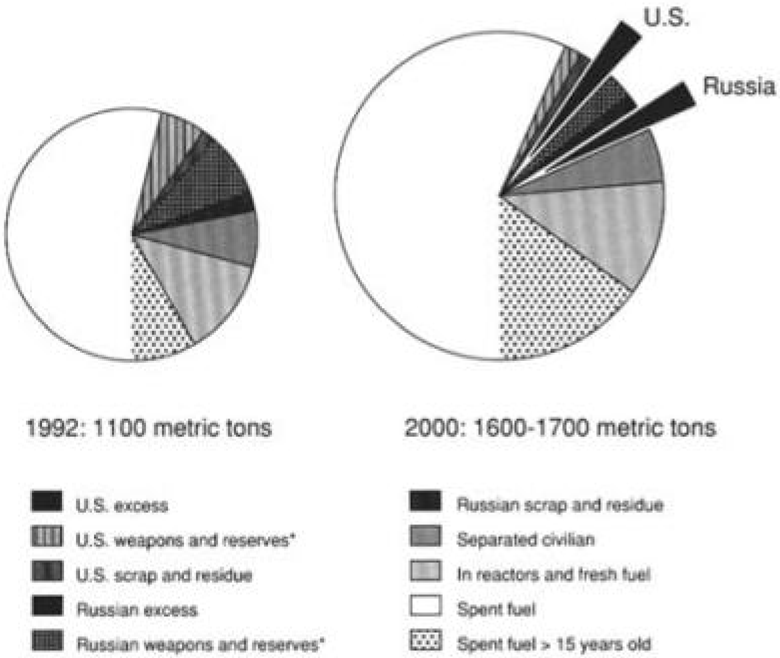

FIGURE 1-3 World plutonium stockpiles

Several kilograms of separated weapons-grade plutonium and a somewhat larger amount of "reactor-grade" plutonium—a minuscule fraction of the world stock—would be enough to build a nuclear weapon. Thus, the plutonium in a truckload of spent fuel rods from a typical power reactor is enough for one or more nuclear weapons. The plutonium stored at a typical civilian reactor site or reprocessing plant is enough for hundreds of weapons.

Plutonium customarily used in nuclear weapons (weapons-grade plutonium) and plutonium separated from spent reactor fuel (reactor-grade plutonium)

[9] See David Albright, Frans Berkhout, and William Walker, *WorldInventory of Plutonium and Highly Enriched Uranium 1992*, (London: Oxford University Press for SIPRI, 1993); and Appendix B of this report. The IAEA has recently estimated, based on reports from the member states, that 86 tons of civilian separated plutonium was in store as of the end of 1992. This figure is expected to grow substantially during the course of the decade. See J.S. Finucane, "Summary: Advisory Group Meeting on Problems Concerning the Accumulation of Separated Plutonium," IAEA, Division of Nuclear Fuel Cycle and Waste Management, September 1993.

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have different isotopic compositions. Plutonium of virtually any isotopic composition, however, can be used to make nuclear weapons.[10] Using reactor-grade rather than weapons-grade plutonium would present some complications. But even with relatively simple designs such as that used in the Nagasaki weapon—which are within the capabilities of many nations and possibly some subnational groups—nuclear explosives could be constructed that would be assured of having yields of at least 1 or 2 kilotons. With more sophisticated designs, reactor-grade plutonium could be used for weapons having considerably higher minimum yields. Thus, the difference in proliferation risk posed by separated weapons-grade plutonium and separated reactor-grade plutonium is small by comparison to the difference between separated plutonium of any grade and unseparated material in spent fuel (see "Reactor-Grade and Weapon-Grade Plutonium in Nuclear Explosives," p. 32.)

Unseparated material, however, also poses some risk. The chemistry for separating plutonium from spent fuel is described in the open literature, and the essential technologies are available on the open market. Although separating plutonium on a commercial scale at competitive prices is difficult and costly, a potential proliferator could use a much simpler and less costly facility to extract enough material for a few weapons. Moreover, the intense radioactivity that initially makes the fuel effectively impossible to handle without remote-handling equipment decays substantially over the decades after the fuel leaves the reactor. (See "How Accessible Is Plutonium in Spent Fuel?" in Chapter 6, p. 150.) Plutonium, whether in "military" or "civilian" stockpiles, and whatever its physical, chemical, or isotopic form, must be strictly safeguarded.

Although plutonium and HEU can both be used to make nuclear weapons, there are several differences between them, of which two are particularly important here. The first is that HEU can be diluted with other, more abundant, naturally occurring isotopes of uranium to make low-enriched uranium (LEU), which cannot sustain the fast-neutron chain reaction needed for a nuclear explosion.[11] LEU is the fuel for most of the world's nuclear power reactors. In contrast, plutonium cannot be diluted with other isotopes of plutonium to make

[10] An exception is Plutonium-238 (Pu-238), which generates too much heat to make fashioning a weapon from it practicable. Pu-238 is a rare and difficult-to-produce isotope, however, used primarily for powering certain types of space probes. Similarly, it would be difficult to fashion a workable weapon of Pu-242, another relatively rare isotope.

[11] Natural uranium includes only 0.7 percent Uranium-235 (U-235), with almost all of the remaining 99.3 percent being U-238, whose atoms will not sustain a nuclear chain reaction. (Isotopes are different types of the same chemical element having differing numbers of neutrons—92 protons and 143 neutrons in U-235, and the same number of protons but 146 neutrons in U-238.) To sustain the chain reaction needed for a nuclear explosion, the concentration of U-235 must be greatly increased, a process known as enrichment. Typical weapons-grade uranium is more than 90 percent U-235. Because the various isotopes of an element are essentially identical chemically, enrichment of the fissile isotopes requires techniques that are costly and time-consuming, and for which the technology is not widely available—which provides one of the primary technical barriers to nuclear proliferation. Chain reactions in power reactors, by contrast, can be and have been sustained with natural uranium, although most reactors today use LEU containing 3-5 percent U-235.

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it unusable for weapons. "Re-enriching" LEU to the level needed for weapons requires complex enrichment technology to which most potential proliferators do not have access, while separating plutonium from other elements with which it might be mixed in producing fresh reactor fuel requires only straightforward chemical processing. Thus, management of plutonium in any form requires greater security than does the management of LEU.

Second, as noted earlier, in the current fuel market, the use of plutonium fuels is generally more expensive than the use of widely available LEU fuels—even if the plutonium itself is "free"—because of the high fabrication costs resulting from plutonium's radiological toxicity and from the security precautions required when handling it. As a result, although most of the world's roughly 400 nuclear reactors could in principle burn plutonium in fuel containing a mixture of uranium and plutonium (mixed-oxide or MOX fuel), only a few, and none in the United States, are currently licensed to do so.

Because of HEU's commercial value and the possibility of diluting it so as not to pose major proliferation risks, its disposition can be addressed by the market. The United States has agreed to buy 500 tons of surplus Russian HEU, blended to LEU, for $11.9 billion over the next 20 years, provided certain conditions are met. The United States will later resell the material to fulfill the demand for nuclear fuel on the domestic and world markets. Although it is possible that a purchase of Russian plutonium could also be justified on security grounds, both the security aspects and the economics of using plutonium as reactor fuel would be less attractive than in the case of LEU (see Chapter 5).

RISKS AND STANDARDS

None of the policy options for managing the dismantlement of excess nuclear weapons and the storage and disposition of the resulting fissile materials plutonium can entirely eliminate the risks these items pose. Standards must be set by which to judge whether the remaining risks are acceptable. In the security area, two complementary standards suggest themselves.

The Stored Weapons Standard. Options should be designed to avoid any *increase* in the risk of proliferation as a result of arms reductions, which could result if weapons and materials become more accessible to theft during the processes involved in dismantlement, storage, and disposition. Thus, to the extent possible, the high standards of security and accounting applied to storage of intact nuclear weapons should be maintained for these materials throughout these processes. The various processing steps will unavoidably make accounting more difficult than in the case of assembled weapons, and it may also be institutionally difficult to preserve the strict security arrangements associated with nuclear weapons themselves. But precisely because of the difficulty of the task, it is important to preserve the goal.

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REACTOR-GRADE AND WEAPONS-GRADEPLUTONIUM IN NUCLEAR EXPLOSIVES

Virtually any combination of plutonium isotopes—the different forms of an element having different numbers of neutrons in their nuclei—can be used to make a nuclear weapon. Not all combinations, however, are equally convenient or efficient. The most common isotope, Pu-239, is produced when the most common isotope of uranium, U-238, absorbs a neutron and then quickly decays to plutonium. It is this plutonium isotope that is most useful in making nuclear weapons, and it is produced in varying quantities in virtually all operating nuclear reactors.

As fuel in a reactor is exposed to longer and longer periods of neutron irradiation, higher isotopes of plutonium build up as some of the plutonium absorbs additional neutrons, creating Pu-240, Pu-241, and so on. Pu-238 also builds up from a chain of neutron absorptions and radioactive decays starting from U-235.[1] Because of the preference for relatively pure Pu-239 for weapons purposes, when a reactor is used specifically for creating weapons plutonium, the fuel rods are removed and the plutonium is separated from them after relatively brief irradiation (at low "burnup"). The resulting "weapons-grade" plutonium is typically about 93 percent Pu-239. Such brief irradiation is quite inefficient for power production, so in power reactors the fuel is left in the reactor much longer, resulting in a mix that includes more of the higher isotopes of plutonium ("reactor-grade" plutonium).

Use of reactor-grade plutonium complicates bomb design for several reasons. First and most important, Pu-240 has a high rate of spontaneous fission, meaning that the plutonium in the device will continually produce many background neutrons. Second, the isotope Pu-238 decays relatively rapidly, thereby significantly increasing the rate of heat generation in the material. Third, the isotope Americium-241 (which results from the 14-year half-life decay of Pu-241 and hence builds up in reactor-grade plutonium over time) emits highly penetrating gamma rays, increasing the radioactive exposure of any personnel handling the material.

In a nuclear explosive using plutonium, the plutonium core is initially "subcritical," meaning that it cannot sustain a chain reaction. Chemical high explosives are used to compress the plutonium to higher than normal density (so that the neutrons released in each fission have a higher probability of hitting other atoms and causing more fissions). In a well-designed nuclear explosive using weapons-grade plutonium, a pulse of neutrons is released to start this chain reaction at the optimal moment, but there is some chance that a background neutron from spontaneous fission of Pu-240

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will set off the reaction prematurely. With reactor-grade plutonium, the probability of such "pre-initiation" is very large. Pre-initiation can substantially reduce the explosive yield, since the weapon may blow itself apart and thereby cut short the chain reaction that releases the energy. Calculations demonstrate, however, that even if pre-initiation occurs at the worst possible moment (when the material first becomes compressed enough to sustain a chain reaction), the explosive yield of even a relatively simple device similar to the Nagasaki bomb would be of the order of one or a few kilotons. While this yield is referred to as the "fizzle yield," a 1-kiloton bomb would still have a radius of destruction roughly one-third that of the Hiroshima weapon, making it a potentially fearsome explosive. Regardless of how high the concentration of troublesome isotopes is, the yield would not be less. With a more sophisticated design, weapons could be built with reactor-grade plutonium that would be assured of having higher yields.[2]

Dealing with the second problem with reactor-grade plutonium, the heat generated by Pu-238 and Pu-240, requires careful management of the heat in the device. Means to address this problem include providing channels to conduct the heat from the plutonium through the insulating explosive surrounding the core, or delaying assembly of the device until a few minutes before it is to be used.

The radiation from Americium-241 means that more shielding and greater precautions to protect personnel might be necessary when building and handling nuclear explosives made from reactor-grade plutonium. But these difficulties are not prohibitive.

In short, it would be quite possible for a potential proliferator to make a nuclear explosive from reactor-grade plutonium using a simple design that would be assured of having a yield in the range of one to a few kilotons, and more using an advanced design. Theft of separated plutonium whether weapons-grade or reactor-grade, would pose a grave security risk.

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[1] For a useful figure showing the buildup of these isotopes as a function of irradiation time, see J. Carson Mark, "Explosive Properties of Reactor-Grade Plutonium," *Science and Global Security*, Vol. 4, no. 1, 1993, pp. 111-128.

[2] See W. G. Sutcliffe and T.J. Trapp, eds., *Extraction and Utilityof Reactor-Grade Plutonium for Weapons*, Lawrence Livermore National Laboratory, UCRL-LR-115542, 1994 (S/RD). For unclassified discussions, see J. Carson Mark, op. cit.

The Pu-240 content even in weapons-grade plutonium is sufficiently large that very rapid assembly is necessary to prevent preinitiation. Hence the simplest type of nuclear explosive, a "gun type," in which the optimum critical configuration is assembled more slowly than in an "implosion type" device, cannot be made with plutonium, but only with highly enriched uranium, in which spontaneous fission is rare. The makes HEU an even more attractive material than plutonium for potential proliferators with limited access to sophisticated technology. Either material can be used in an implosion device.

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The Spent Fuel Standard. Options for the long-term disposition of weapons plutonium should seek to meet a "spent fuel standard"—that is, to make this plutonium roughly as inaccessible for weapons use as the much larger and growing stock of plutonium in civilian spent fuel. Options that left the weapons plutonium more accessible would mean that this material would continue to pose a unique safeguards problem indefinitely. Conversely, the costs, complexities, risks, and delays of going beyond the spent fuel standard to eliminate the excess weapons plutonium completely or nearly so would not offer substantial additional security benefits *unless society were preparedto take the same approach with the global stock of civilian plutonium.*

This standard, if accepted, has a profound impact on the choice of long-term disposition options. Approaches that would leave the plutonium in a form substantially more accessible for recovery and use in weapons than plutonium in commercial spent fuel can be rejected, and substantially costlier, riskier, or slower options for eliminating the weapons plutonium or making it less accessible than plutonium in spent fuel should be considered only in the larger context of similar treatment of all of the world's plutonium stock.

Beyond the Spent Fuel Standard. The spent fuel standard should not be interpreted as an endorsement of today's standards of management for plutonium in spent fuel, however. Although substantially less accessible for use in weapons than separated plutonium, plutonium in spent fuel does pose a security risk, and that risk increases with time, as noted above. Further steps should be taken to reduce the proliferation risks posed by *all* of the world's plutonium stocks, military and civilian, separated and unseparated; the need for such steps exists already, and will increase with time (see Chapter 6).

THE INSTITUTIONAL FRAMEWORK

The institutional and political issues involved in managing weapons dismantlement, intermediate storage of fissile materials, and long-term disposition may be more complex and difficult to resolve than the technical ones. Because disposition options will require decades to carry out, it is critical that decisions throughout be made in a way that can muster a sustainable consensus. The entire process must be carefully managed to provide adequate safeguards, security, and transparency; to obtain public and institutional approval, including licenses; and to allow adequate participation in the decision making by all affected parties, including the U.S. and Russian publics and the international community. Adequate information must be made available to give substance to the public's participation.

These issues cover a broad institutional and technical spectrum. Establishing fully developed arrangements for managing these tasks will require an unusually demanding integration of policy under conditions of dispersed authority and intense political sensitivity. In the United States, jurisdiction over fissile

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material and fabricated weapons is divided between the Department of Energy (DOE) and the Department of Defense (DOD) in different phases of the deployment cycle. Each department has many subordinate divisions involved. Related diplomacy is handled by the State Department and the Arms Control and Disarmament Agency, with input from DOE and DOD. Numerous other agencies perform supporting functions. The relevant installations are authorized and financed by Congress, regulated by independent agencies and commissions, constrained by state laws, and increasingly affected by public opinion in their surrounding communities. Policy debates too often focus on specific options, such as particular reactor types, rather than the comprehensive view required to make choices for this complex problem. The consequences of this fragmentation are illustrated in a related area by the fact that technical assessment of the U.S. high-level waste repository at Yucca Mountain is incomplete after two decades of work and billions of dollars of expenditure, and final licensing is not projected for another two decades. These challenges to comprehensive policymaking are at least as great in Russia, where they must be surmounted in the midst of continuing political and economic upheaval.

None of the governments involved have previously faced the problem of handling excess plutonium in the quantities now contemplated, and none appear to have developed policies and procedures likely to be adequate to the task. Yet decisions are urgent, since without new approaches even the near-term tasks of dismantlement and storage are not likely to meet all of the required security criteria.

In these areas, the United States bears a special burden of policy leadership. If demanding technical assessments are to be completed, if consensus is to be forged, and if implementation is to be accomplished in reasonable time, major advances in the formulation and integration of policy and in institutional coordination will be needed. The president should establish a more systematic process of interagency coordination to deal with the areas addressed in this report, with sustained top-level leadership. The new interagency examination of plutonium disposition options envisioned in President Clinton's September 27, 1993, nonproliferation initiative is a first step in that direction, but much more remains to be done.

THE ROLE OF ENVIRONMENT, SAFETY, AND HEALTH

The history of the U.S. and Russian nuclear weapons complexes is replete with instances where production in the name of national security took priority over environment, safety, and health (ES&H) concerns. The result is a heritage of environmental damage whose dimensions are only now becoming apparent. Remedial actions are just beginning and will continue for decades. The United States committed about $6 billion from the Department of Energy budget for Fiscal Year 1993 for these purposes, and some estimates of the eventual cost

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run to hundreds of billions of dollars. In the former Soviet Union, the ES&H damage appears to be even more severe.

In reaction to this legacy, new and stringent ES&H regulations are being imposed on the U.S. nuclear weapons complex. Environmental advocates are seeking comparable requirements in Russia. These are dynamic standards, and can be expected to change over time with increasing knowledge about long-term effects and remedies, and with varying public awareness and willingness to accept environmental risks.

Currently, ES&H requirements set the pace for each of the stages of dismantlement, storage, and disposition. For example, new standards have roughly doubled the time it takes to dismantle a nuclear weapon at Pantex, the U.S. facility. The choice of intermediate weapons storage options and the time required to implement such choices are heavily influenced by the licensing and approval process, including the extended safety and environmental analyses required for each option.

Ultimately, these ES&H standards affect the ease and cost of achieving different disposition options and may have a significant impact on the choices among them. This report does not attempt to evaluate the benefits and costs of this evolving regulatory framework. Instead, for each option, the potential impact of the ES&H framework is simply assessed as realistically as possible, as one important factor guiding policy choices.

Fundamentally, ES&H and arms control seek the same goal: minimizing threats to human well-being, whether from nuclear explosions or from environmental and occupational hazards. It would be unfortunate, therefore, if arms control and ES&H concerns came to be pitted against each other (as they have become, to some extent, in the parallel debate over chemical weapons destruction). There are bound to be disagreements about specific issues among those who bring differing perspectives to these problems. But the committee believes that the goals of security and protection for ES&H can be achieved without significantly compromising either objective. What is needed is a consistent, risk-based approach that integrates ES&H and security concerns, and focuses finite ES&H resources on the most urgent problems and the most promising means for addressing them.

PLAN OF THE STUDY

The organization of this report reflects the goals and approaches described above. Chapters 1, 2, and 3 set the stage. Chapter 2 describes the international context in which policy choices with respect to dismantlement, storage, and disposition must be made, including the crisis in the former Soviet Union, the arms reduction and nonproliferation regimes, ongoing civilian plutonium programs, and existing standards of safeguards and security for fissile materials. Chapter 3 describes in more detail the criteria for judging policy choices. The three stages of the process of reductions are described in the three "action"

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chapters: Chapter 4 addresses dismantlement, and the related question of an overall regime to limit and monitor the size of stockpiles of nuclear weapons and fissile materials; Chapter 5 addresses requirements and choices related to the storage of plutonium, and the related issue of measures to reduce the accessibility of fissile materials in the former Soviet Union; and Chapter 6 discusses the options for long-term disposition of the plutonium from dismantled weapons. Finally, Chapter 7 summarizes the committee's recommendations.

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International Context

The management and disposition of plutonium from dismantled nuclear weapons will take place within a complex international context that includes the arms reduction and nonproliferation regimes of which this problem is a part; the continuing crisis in the former Soviet Union; worldwide plans for civil nuclear energy, particularly the use of separated plutonium; and existing approaches to safeguards and security for nuclear materials. This context must be understood in considering policy options for excess military plutonium.

PLANNED NUCLEAR ARMS REDUCTIONS: HOW MUCH PLUTONIUM AND WHEN?

Recent nuclear arms reduction agreements and pledges, if successfully implemented, coupled with national decisions concerning how much plutonium is to be declared "excess" to military needs, will largely set the parameters of how much excess plutonium will require disposition and when it will become available.

The Scope of Reductions

Under the first and second Strategic Arms Reduction Treaties (START I and START II), the operational U.S. strategic stockpile is slated to decline from just over 12,500 weapons in early 1991 to 3,500 weapons after the turn of the century. The Russian strategic stockpile is to be reduced from more than 10,500 weapons to 3,500 or fewer over the same period. These treaties do not commit either side to dismantle the nuclear weapons to be retired under their provisions,

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though it appears that each nation will unilaterally (or, in the Russian case, in coordination with Ukraine, Kazakhstan, and Belarus) choose to dismantle a significant fraction of them.

Tactical nuclear reductions on a similar scale are now under way, as a result of unilateral pledges made by Presidents Bush, Gorbachev, and Yeltsin, rather than U.S.-Russian (or U.S.-Soviet) agreements.[1] The U.S. government has officially indicated that it possessed roughly 8,000 tactical nuclear warheads in its operational stockpile as of 1992 and plans to retain only 1,600 of these. The remaining 6,400 warheads are presumably subject to destruction under President Bush's unilateral commitment. The actual number of Russian tactical weapons to be eliminated under Russia's unilateral reduction pledges is difficult to judge; the Central Intelligence Agency (CIA) has publicly estimated that the figure is between 5,000 and 12,000.[2]

Thus, on the U.S. side, as many as 15,000 tactical and strategic weapons are likely to be retired within a decade. The amount of fissile material in these weapons is classified. For the purposes of this study, the committee uses 4 kilograms of plutonium per weapon as a planning figure.[3] This would suggest that the weapons slated for retirement contain some 60 tons of plutonium. The Department of Energy (DOE) has recently stated publicly that "up to approximately 50 metric tons of plutonium will (or may) become available by about 2005 … [for] civilian (unclassified) purposes," from both weapons and other sources.[4]

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[1] In September 1991, President Bush announced that the United States would withdraw all of its ground- and sea-launched tactical nuclear weapons to the United States, and that all of the ground-launched and roughly half the sea-launched weapons would be eliminated. The following month, Soviet President Mikhail Gorbachev announced that all tactical nuclear weapons would be withdrawn to Russia, and that nuclear artillery, ground-launched missile warheads, and nuclear mines would be destroyed. In January 1992, Russian President Yeltsin confirmed and extended Gorbachev's commitments. In addition to destroying all ground-launched tactical warheads, he stated that Russia would destroy half of its tactical air-launched nuclear warheads, one-half of its nuclear warheads for antiaircraft missiles, and one-third of its tactical sea-launched nuclear warheads. Russian officials have since stated that the sea-based, air-delivered, and air defense weapons will be dismantled by 1996, the nuclear mines by 1998, and all other land-based tactical weapons by the year 2000.

[2] See Lawrence Gershwin, National Intelligence Officer for Strategic Programs, *DOD Appropriations for FY1993*, testimony before the House Committee on Appropriations, Part 5, May 6, 1992, p. 499. In addition, Gershwin estimated that as of that date, 2,700 Russian weapons remained to be dismantled from the Intermediate-Range Nuclear Forces (INF) Treaty. Public estimates of the total Russian stockpile of tactical nuclear weapons range from 15,000 to 21,000; General Colin Powell put the figure at 17,000 in a Defense Department press conference on September 28, 1991 (transcript, *Federal News Service*).

[3] The minimum quantities of plutonium or highly enriched uranium (HEU) needed to make a weapon are not well defined, as they depend on the design. Actual quantities used in U.S. weapons are classified.

[4] Lou Willett, Deputy Director, Office of Weapons and Materials Planning, Defense Programs, U.S. Department of Energy, "Excess Fissile Materials," presented at the Annual Meeting of the American Power Conference, Chicago, Illinois, April 13-15, 1993. The uncertainty implied by the parenthetical "(or may)" reflects continuing debate within the U.S. government over how much of these materials should be kept as military reserves. On December 7, 1993, the Department of Energy announced that 102 tons of plutonium had been produced for the U.S. military stockpile (including 89 tons of weapons-grade material and 13 tons of fuel-grade), of which 33.5 tons was held in various forms at several nuclear weapons complex sites, leaving some 68.5 tons currently in weapons or in disassembled weapons components at the Pantex dismantlement site.

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As noted, the corresponding Russian total reduction figures are even more uncertain. Adding some 6,500 strategic weapons to be retired under START I and START II to the CIA's figures for tactical weapons would bring the total number of weapons to be retired on the Russian side to between 14,000 and 22,000. Assistant Secretary of Defense Ashton Carter provided a figure in the middle of this range in mid-1993, testifying that Russia plans to dismantle 18,000 weapons.[5] Using the same planning figure would suggest that these weapons contain more than 70 tons of plutonium. But if the initial Soviet stockpile was as high as some estimates suggest and Russia does not choose to retain a tactical nuclear force significantly larger than the force the United States plans, the number of weapons to be retired could be substantially higher, amounting to perhaps 30,000 or more.[6]

As in the U.S. case, some of these weapons or materials may be retained for reserves and stockpile support rather than being considered excess, while some existing stocks of fissile material from other sources may also be excess. In particular, Russian statements suggest that Russia has substantial stocks of highly enriched uranium (HEU) in addition to the materials incorporated in weapons.[7] Overall, the Russian government has indicated that it expects to have 50 tons of plutonium and 500 tons of HEU that are excess to its military needs, but these figures may grow.

[5] House Foreign Affairs Committee, September 21, 1993 (transcript, *Federal News Service*). A mid-1992 Russian statement suggests a somewhat higher figure for the number of weapons to be dismantled: Victor Mikhailov, head of the Russian Ministry of Atomic Energy (MINATOM), reportedly indicated that the Russian stockpile would decline to 40-50 percent of its mid-1992 level as a result of arms control initiatives through early 1992. Given previous Mikhailov statements concerning the size of that stockpile, this suggests a reduction of 17,000-21,000 warheads, to which must be added several thousand warheads resulting from START II, signed subsequent to Mikhailov's remarks. See discussion in Thomas B. Cochran and Robert S. Norris, *Russian/Soviet NuclearWarhead Production* (Washington, D.C.: Natural Resources Defense Council, September 8, 1993), p. 23.

[6] Mikhailov has estimated that as of 1986, the Soviet Union possessed some 45,000 nuclear warheads, of which 13,000 have already been dismantled. See Cochran and Norris, op. cit.; and William Broad, "Russian Says Soviet Atom Arsenal Was Larger Than West Estimated," *The New YorkTimes*, September 26, 1993. Mikhailov's figures are higher than most U.S. estimates; Secretary of Energy Hazel O'Leary has been quoted as saying: "I don't believe those numbers and I think he knows we don't believe those numbers." See Dunbar Lockwood, "Report on Soviet Arsenal Raises Questions, Eyebrows," *Arms Control Today*, November 1993. Assistant Secretary of Defense Ashton Carter indicated in testimony on September 21, 1993 (House Foreign Affairs Committee, op. cit.) that the current U.S. estimate is that the total Soviet stock is between 25,000 and 35,000 warheads, the high end of which is consistent with Mikhailov's figures. If Mikhailov is correct, and Russia chose to retain an arsenal comparable to the planned 5,100-warhead active U.S. arsenal, with minimal reserves, the total reduction from the peak level would amount to some 40,000 weapons.

[7] In an interview in the fall of 1993, Mikhailov indicated that the 500 metric tons of HEU involved in the U.S.-Russian HEU deal "represents somewhere around 30 to 40 percent of all reserves that we possess," suggesting a total stockpile of at least 1,250 tons of HEU. Mikhailov has reportedly used similar figures in discussions with U.S. DOE officials. There is considerable uncertainty in the United States concerning whether this figure is accurate; the article based on the interview reports that previous U.S. intelligence estimates were in the range of 800 tons. See Elizabeth Martin, "A Conversation with Viktor Mikhailov," *NUKEM Market Report*, October 1993.

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Reduction Schedules

The schedule on which these excess materials become available and therefore require intermediate storage will be determined by the rate at which weapons are retired and dismantled. A considerable amount of excess fissile material already exists—amounting to tens of tons of plutonium—from previously dismantled weapons and other sources within each side's weapons complex. For example, more than 5,000 plutonium "pits"—plutonium weapons components—from dismantled weapons were already stored at the Pantex plant in Amarillo, Texas, as of late 1993.[8]

Dismantlement of weapons already retired is continuing on both sides, in the United States at a rate of somewhat less than 2,000 weapons per year, and in Russia at an unknown but reportedly comparable rate. Dismantlement issues are discussed in detail in Chapter 4.

On both sides, the planned withdrawals of tactical weapons based abroad are now complete,[9] and thousands of weapons are available to be dismantled as fast as the dismantlement facilities can process them. Both sides have also retired a significant number of strategic weapons, although the START I and START II treaties are not yet in force. The schedule for further retirements of strategic weapons, however, is more complex (see Figure 2-1).

START I calls for three phases of reductions over seven years (starting from the treaty's entry into force, which now will not occur before early 1994 at best), whereas START II calls for two phases, the first over START's seven-year span and the second to be completed by 2003. If the two sides reduced no faster than legally required by START I and START II, the bulk of the strategic reductions required under these treaties would come just after the turn of the century, to meet START II limits.[10]

If START I entered into force in early 1994, its second phase of reductions would end in early 1999. By that time, each side would have been required to reduce its forces to 7,950 total "accountable" deployed warheads, of which

[8] Until 1989, when the Rocky Flats plant closed, pits were shipped there to be fashioned into pits for new weapons. Since these shipments were stopped, more than 4,000 weapons have been dismantled. See U.S. Department of Energy, Albuquerque Operations Amarillo Area Office, "Environmental Assessment for Interim Storage of Plutonium Components at Pantex," Predecisional Draft, December 1992, p. 2-2. For specific figures on dismantlement since 1989, see Chapter 4; and U.S. Congress, House Appropriations Subcommittee on Energy and Water Development, *Energy and Water Development Appropriations for 1994*, Part 6, p. 1308.

[9] By mid-1992, the United States had met its commitment to withdraw ground-launched and sea-launched tactical weapons to the United States. Russia has also apparently succeeded in withdrawing the former Soviet tactical warheads to its territory on schedule: On May 6, 1992, the Russian government officially announced that all tactical nuclear weapons had been removed to Russia from Ukraine, the last non-Russian state in which they were deployed, and on February 3, 1993, the Russian Ministry of Defense reported that all former Soviet tactical nuclear weapons from ships and submarines had been withdrawn to Russia. Despite many rumors of "loose nukes," there appears to be no serious basis for questioning these Russian announcements.

[10] Although START II requires that reductions be "sustained throughout the reductions period," there are no annual requirements except in the case of the SS-18. The U.S. State Department's analysis of the accord emphasizes that the term "sustained" does not imply "straight-line" reduction rates, and that this is not a "specific legal obligation to reduce at a given rate." See U.S. Senate, *Treaty with the RussianFederation on Further Reduction and Limitation of Strategic OffensiveArms (The START II Treaty)*, Treaty Document 103-1, 1993.

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6,750 could be carried by ballistic missiles. Since U.S. operational strategic forces are already close to the final levels mandated by START I, and will meet those levels by the end of 1994, this second-phase limit would not require any further reductions in U.S. forces between 1994 and 1999. By contrast, over the same period, Russian deployed strategic forces would be reduced by 20 percent.

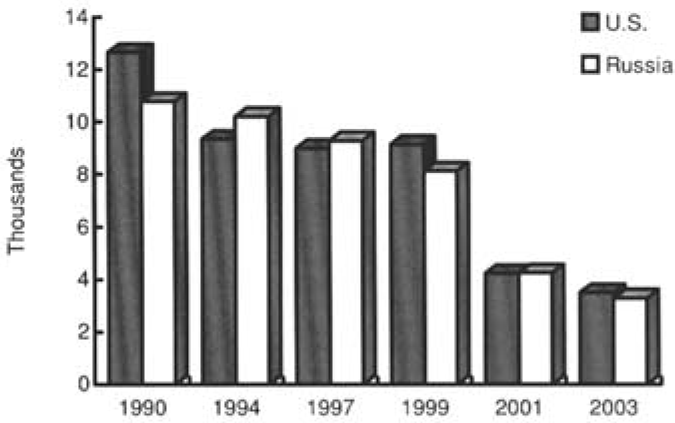

FIGURE 2-1 Forces under START I and II: United States and Russia

In early 2001 the force levels of the first phase of START II would supersede the final force levels of START I, requiring cuts to 4,250 *actual* warheads on each side. This would be a reduction in just two years of approximately 50 percent in projected U.S. forces and somewhat less on the Russian side (though with more emphasis on missile cutbacks). Moreover, by 2001, all remaining nuclear weapons would be removed from Ukraine, Kazakhstan, and Belarus.

In the second and final phase of START II, actual U.S. and Russian warheads would have to undergo another reduction of approximately 18 percent, to reach the final ceiling of 3,500 warheads. Thus, in the four years from 1999 to 2003, U.S. forces would be reduced by more than 60 percent, and Russian forces by 55 percent. This uneven pace of reductions could be smoothed out if each side continued to carry out reductions sooner than it is legally required to do so.

THE CRISIS IN THE FORMER SOVIET UNION

The demise of the Soviet Union and the ongoing political and economic crises in the former Soviet states raise substantial risks for arms reduction and nonproliferation.

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A key goal of the denuclearization process is ensuring that the organizations charged with managing nuclear weapons, materials, and technology—including the military, the Ministry of Atomic Energy (MINATOM), and the relevant regulatory agencies—can carry out the responsibilities assigned to them on the schedule envisioned, while preventing leakage of nuclear weapons, materials, and technologies to potential proliferators. This challenge must be met amidst a crisis-prone political transformation and deep economic trauma. The tasks must be accomplished by complex institutions accustomed to operating under a central authority that has been fundamentally weakened, and with central missions and guidelines defined by a Cold War confrontation that has now vanished. In effect, Russia, like the United States, must now run its nuclear weapons complex in reverse—dismantling thousands of nuclear weapons each year rather than assembling them; disposing of plutonium and HEU rather than producing more; and fostering transparency and trust, rather than maintaining strict secrecy. This fundamental change of mission must be carried out in both countries by institutions operating with obsolete and contaminated facilities and declining budgets, while grappling with new demands for transparency and public accountability, and suffering from a lack of public credibility and acceptance.

The current crisis in the former Soviet Union creates a variety of risks with respect to the management and disposition of nuclear weapons and fissile materials. This report categorizes these as dangers of:

- "breakup," meaning the emergence of multiple nuclear-armed states where previously there was only one;
- "breakdown," meaning erosion of government control over nuclear weapons and materials within a particular state; and
- "breakout," meaning repudiation of arms reduction agreements and pledges, and reconstruction of a larger nuclear arsenal.

Ideas for reducing these risks related to management of nuclear weapons and fissile materials are discussed in Chapter 4 and 5.

The Risks of Breakup

If more than one nuclear state emerges from the demise of the Soviet Union, it would almost certainly prevent implementation of START I and II, unraveling the arms reduction regime they represent. It could also deal a devastating blow to global nonproliferation efforts and put the results of the 1995 conference to extend the nuclear Non-Proliferation Treaty (NPT) in doubt. Over the long term, nearby countries might reconsider their nonnuclear commitments. If North Korea took the nuclear road at the same time, the entire nonproliferation regime could be called into question.

Ukraine, Belarus, Kazakhstan, and Russia are the only states on whose territory nuclear weapons of the former Soviet Union are still deployed. In the

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Lisbon Protocol of May 1992 and accompanying letters, the three non-Russian states agreed to eliminate the nuclear weapons on their soil as part of the START I reductions, and to join the Non-Proliferation Treaty as non-nuclear-weapon states "in the shortest possible time," leaving Russia as the sole inheritor of the Soviet Union's nuclear weapons. Belarus has acceded to the NPT, and in the fall of 1993, Kazakhstan reiterated its pledge to do so quickly, but Ukraine has not. The U.S. Senate, the Russian Supreme Soviet, and the Kazakh and Belarusan parliaments have approved START I. As noted in Chapter 1, Ukraine poses the greatest risk, as there are a growing number of voices in that country raising questions about the wisdom of eliminating the nuclear weapons now on Ukrainian soil, and in November 1993, the Ukrainian Rada acted to ratify START without accepting the denuclearization commitment of the Lisbon Protocol. Efforts to resolve the issue are continuing, but Ukraine's ultimate decision remains in doubt.

The Risks of Breakdown

The risks of theft of nuclear weapons or fissile materials in the former Soviet Union are serious. The Soviet Union maintained an elaborate system of security and command and control to ensure against any unauthorized seizure or use of nuclear weapons, and the Russian government is trying to maintain this system.[11] Controls over fissile materials were traditionally based primarily on extensive physical security measures, rather than detailed accounting, and this continues to be the basic approach. The overall integrity of these systems is difficult to determine, particularly since their heavy reliance on secrecy limits the information available to the public.

For now, the U.S. intelligence community is confident that the nuclear weapons of the former Soviet Union remain under firm central control and security.[12] Fissile materials pose a more difficult question. The intelligence community continues to check out each report of theft, transfer, or sale of nuclear weapons or fissile materials, but has "not, to this point, detected the sale or transfer of significant nuclear material, nor the sale or transfer of the weapons themselves." [13] But not all reports have been successfully tracked down. Given the level of social turbulence in Russia, control over weapons and materials could erode over time. Already, there are dozens of reports of events suggesting some erosion of the organizations involved in controlling these materials. These include large-scale military corruption and extensive thefts of conventional weapons, myriad cases of theft of civilian nuclear materials,

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[11] For a current description, see Bruce Blair, *The Logic of AccidentalNuclear War* (Washington, D.C.: The Brookings Institution, 1993).

[12] See, for example, testimony of CIA Director R. James Woolsey, House Foreign Affairs Committee, July 28, 1993. Weapons outside of Russia are under Russian operational control. Those in Ukraine, however, raise greater concerns. If the dispute with Russia over Ukraine's denuclearization commitments and related issues worsens, Ukraine might attempt to assert physical control over them.

[13] Woolsey, ibid.

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threats by Strategic Rocket Forces personnel to leave their posts because of inadequate food supplies, protests and threats of strikes at nuclear weapons facilities where personnel have not been paid in months, and military factions apparently operating quasi-independently in various conflicts on Russia's borders.

Nuclear weapons and weapons-usable fissile materials are likely to be under considerably tighter security than conventional weapons and less strategically significant nuclear materials. But Minister of Atomic Energy Mikhailov has confirmed one theft of HEU and two thefts of low-enriched uranium (LEU). There are some press reports that purport to have confirmation of black market dealers possessing weapons-grade plutonium. Mikhailov and other responsible Russian officials have acknowledged the increasing risks of materials theft created by the current economic and social turmoil in Russia, and have suggested a variety of means to strengthen procedures to cope with the issue.[14] Guards at

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[14] There are many hundreds of reports of various types of theft of nuclear materials, most of them speculative or inaccurate. (For a partial chronology, see William C. Potter, *Nuclear Profiles ofthe Soviet Successor States* (Monterey, Calif.: Monterey Institute of International Studies, May 1993), Appendix One.) Only those in which some confirmation is available, preferably from responsible Russian officials, are discussed here.

For Mikhailov's references to material thefts, see Elizabeth Martin, "A Conversation with Viktor Mikhailov," *NUKEM Market Report*, October 1993. It was not clear from the interview whether the stolen material was recovered. Mikhailov acknowledged that "many people in Russia live on the edge of poverty and there is a great temptation to steal in these plants," requiring strengthened "procedures for accounting and control of all aspects of the fuel cycle." Similarly, Aleksandr Mokhov, head of MINATOM's Administration for Protection of Information, Nuclear Materials, and Sites, has acknowledged three cases of theft of uranium in the last two years (from facilities at Podolsk, Glazov, and Arzamas-16). Up until 1990, according to Mokhov, only three similar thefts had been recorded, in 1967, 1971, and 1989. Mokhov did not indicate whether the uranium involved in these cases was HEU, LEU, or unenriched material. He indicated that there have been no reported thefts or attempted thefts of plutonium, but acknowledged that "discipline and responsibility among some managers and staff at enterprises, including our specialized services, has deteriorated." See Veronika Romanenkova, "Atomic Energy Official Views Recent Uranium Thefts," ITAR-TASS World Service, February 20, 1993, reprinted in *ForeignBroadcast Information Service—Central Eurasia* (hereinafter FBIS-SOV), February 24, 1993, p. 40.

Several months later, militia Lieutenant General V.P. Ignatov, the head of Interpol's Russian bureau, also confirmed three uranium thefts, but said, "I can state with full responsibility that not a single criminal attempt to steal weapons-grade nuclear materials has been registered at any Russian military industrial installation." All thefts uncovered by law enforcement agencies, he indicated, were of materials "that cannot be used to fabricate weapons." Ignatov warned, however, that "criminals are not abandoning their attempts to steal radioactive materials" and suggested that a new international convention be negotiated "to combat nuclear terrorism." See Veniamin Polubinskiy, "Radioactive Business: Myths and Reality," *Federatsiya*, April 2, 1993, reprinted in FBIS-SOV, April 16, 1993, p. 42.

Similarly, Major-General Gennady Yevstafyev, head of the division of the Russian foreign intelligence service dealing with nonproliferation, stated in August 1993 that "no sign has been found of highly enriched uranium, plutonium, and specific nuclear technologies being illegally exported," but he warned that security standards varied considerably at different types of facilities and that problems in this area would soon become "acute." He suggested setting up an International Atomic Energy Agency (IAEA) group to monitor the illegal nuclear trade. See Vladimir Orlov, "Nuclear Analysis by General Yevstafyev of the Russian Intelligence Service," *Moscow News*, August 27, 1993.

Mikhailov, at roughly the same time as he acknowledged the HEU theft, denied in another interview that any weapons-grade materials had been stolen, saying that reports of such thefts were "somebody's fantasy or a special forgery," designed to "tarnish the nuclear industry and Russia's nuclear complex." Mikhailov was reacting to what was purported to be a police document, reportedly confirmed by the chief investigator in the

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many facilities are reportedly poorly paid and motivated, and may be susceptible to bribery or threats. Some civilian facilities with enough HEU or plutonium for a bomb, such as research reactors, reportedly have no portal monitors to detect removal of fissile material. Diversions directed by officials within a particular facility could effectively bypass most of the security measures that do exist, and cannot be ruled out. Although Russian officials continue to resist the idea that "insider" theft is a serious possibility, cases of theft of LEU involving as many as eight insiders conspiring together have been officially confirmed.[15] Such insider conspiracies pose severe challenges to security systems. The United States (along with some other donors) is planning to provide Russia, Ukraine, Belarus, and Kazakhstan with limited assistance in improving safeguards and security for fissile materials, but much more needs to be done (see Chapter 5).

The Risk of Breakout

The final risk is the danger that the arms reductions process might be reversed—a prospect often referred to as "breakout"—or that perceptions that this danger remained might limit the scope or benefits of reductions. This risk is integrally linked to the overall structure of the arms reduction regime, a part of the context of the plutonium problem addressed below.

THE ARMS REDUCTION REGIME

The committee's previous study described its view of the future of nuclear weapons and nuclear arms reductions in detail.[16] The existing nuclear arms reduction regime is the product of more than 30 years of effort, signifying a recognition by both the United States and the Soviet Union—continued by Russia—that cooperation in limiting military threats serves their security interests better than unbridled competition. Continuing to build on these elements of a cooperative regime will be an important part of U.S. security policy in the

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case, indicating that materials seized from a group of black market arms dealers in Moscow included "weapon-grade plutonium." (The dealers had indicated to an undercover reporter that the material included "80 percent of uranium and 20 percent of plutonium," a ratio typical of breeder reactor fuel.) See Chris Wallace, "Loose Nukes," *Prime-Time Live*, ABC News, October 14, 1993, transcript.

Despite these risks, it appears that MINATOM and the Ministry of Defense are resisting external oversight of security and accounting procedures by GOSATOMNADZOR, the Russian equivalent of the Nuclear Regulatory Commission, which President Yeltsin has charged with that task. See Mark Hibbs, "Watchdogs Say MINATOM Withholding Material Theft and Diversion Data," *Nuclear Fuel*, August 16, 1993; Yevgeniy Solomenko, "Army Smoking Break on Powder Keg," *Izvestia*, July 21, 1993, reprinted in FBIS-SOV, July 21, 1993; and "Uranium, Plutonium, Pandemonium," *The Economist*, June 5, 1993.

[15] At least eight insiders at the factory are said to have been involved in the widely reported Glazov uranium theft, which apparently involved some 100 kilograms of uranium. For a detailed official confirmation of this case, see Veniamin Polubinskiy, "Radioactive Business: Myths and Reality," *Federatsiya*, April 2, 1993, reprinted in FBIS-SOV, April 16, 1993, p. 42. For a listing of other accounts, see Potter, op. cit.

[16] National Academy of Sciences, Committee on International Security and Arms Control, *The Future of the U.S.-Soviet Nuclear Relationship* (Washington, D.C.: National Academy Press, 1991).

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years to come. As the committee argued in its previous study, provided world conditions are favorable and the other nuclear powers can be brought along, substantial reductions beyond the START II levels would further improve security.

A substantial factor limiting the likely scope of reductions is the perceived risk of breakout. Unless the warheads to be retired and other excess warhead stocks are dismantled, and the fissile materials they contain controlled, each party to reductions might fear that another party could rapidly abandon the reductions regime and reconstitute its arsenal.

Despite the uncertain nature of the present Russian political scene, it is difficult to envision a situation in which even an extremely nationalistic future Russian government would choose to repudiate START I and START II once they had entered into force. Moreover, at the levels of highly survivable forces projected for 2003 under START II, even the worst-case breakout scenario on either side would not fundamentally threaten the strategic balance.

Recent agreements, however, do little to reduce the theoretical potential for breakout. Under START I and START II, nearly all of the reductions are to be accomplished simply by removing warheads from launchers that will remain deployed or that will be placed in storage.[17] Once the nuclear weapons are removed from their delivery vehicles, there is no requirement to eliminate, control, or even account for them. These accords generally also do not require elimination of retired missiles, and they place few limits on reserve stocks of nondeployed missiles or nuclear weapons.[18]

Most of START II's large reductions will be achieved by removing warheads from missiles that will remain in service—a process known as "downloading"—and by shifting bombers to conventional missions.[19] Thus, in the unlikely event that either side decided to break out of the START II treaty, much of the job could be done simply by: (1) loading warheads back on to downloaded, but still operational, missiles; (2) reorienting bombers from conventional

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[17] The Intermediate-Range Nuclear Forces (INF) Treaty went somewhat further, requiring the physical destruction of the missiles to be retired (rather than only their launchers) and covering not only deployed systems but nondeployed systems as well. The goal, in part, was to make the agreement stronger and more complete by eliminating all the limited systems. Even in that case, however, there was no requirement for the dismantlement of any of the retired warheads, a fact that provoked some criticism.

[18] The exception is the "heavy" 10-warhead SS-18 intercontinental ballistic missile (ICBM), which Russia has agreed to eliminate under START II. All but 90 of the SS-18 silos must also be destroyed, with the remaining 90 modified so that they can launch only much smaller missiles.

[19] For example, U.S. C-4 and D-5 submarine-launched ballistic missiles (SLBMs), which currently carry 8 warheads, could be downloaded to 4, while remaining equipped with a warhead "bus" capable of carrying 8. In the Russian case, 105 of the SS-19 ICBMs could be downloaded from 6 warheads to 1, and the SS-N-20 SLBM will probably either be downloaded from 10 to 6 warheads or be replaced with a new 6-warhead missile. Only in the case of the SS-18s are all missiles and "reentry vehicle platforms" (buses) to be destroyed. See U.S. Senate, *TreatyBetween the United States and the Union of Soviet Socialist Republicson the Reduction and Limitation of Strategic Offensive Arms*, Treaty Documents 102-20 and 102-32.

Each side can also remove warheads from a limited number of bombers and "reorient" the planes to conventional status, without any modification. The United States plans to invoke this provision for its entire fleet of almost 100 B-1 aircraft.

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to nuclear roles; or (3) reactivating retired missiles in storage. (The third step would be more difficult and time-consuming.) By these means, even after START II was fully implemented, Russia might be able to relatively rapidly increase its force by as much as 100 percent. The United States might be able to increase its force by roughly 130 percent.[20]

Despite the small likelihood of breakout, the continuing option represented by these delivery vehicles and warheads remains a weakness in the current arms reduction regime. This weakness could become more threatening over time if political conditions deteriorate, and could limit the political prospects for further cuts, or for bringing other nuclear states into the reductions process. Approaches to addressing this problem are discussed in Chapters 4 and 5.

THE NONPROLIFERATION REGIME

The global nonproliferation regime also represents decades of effort in building a more cooperative approach to security. Ultimately, restraining the spread of nuclear weapons is a political issue, which must rest on the conviction of states that their security is better served by not acquiring nuclear weapons. Technical barriers alone cannot prevent proliferation by a state determined to acquire nuclear weapons; they can only make it more difficult, costly, and time-consuming—which in some cases can provide the time needed for political persuasion to end a nuclear weapons program. As noted in Chapter 1, the primary technical barrier to nuclear weapons capability remaining today is access to fissile materials. Policies for the management and disposition of existing plutonium must be designed to strengthen this technical barrier, and to help strengthen the agreements and institutions involved in implementing the nonproliferation regime.

Fundamentals of the Nonproliferation Regime

The foundation of the nonproliferation regime is the nuclear Non-Proliferation Treaty, which was signed in 1968 and entered into force in 1970. This treaty, which now has nearly 160 adherents, consists of a fundamental bargain. All of the member nations except the five declared nuclear-weapon states (the United States, Great Britain, France, China, and the former Soviet Union, all of whom are now parties) are prohibited from acquiring nuclear weapons; in return, the nonnuclear states are to have open access to and assistance in nuclear technology for peaceful purposes, and the nuclear-weapon states are to work toward disarmament in good faith. The treaty allows any party to acquire and use separated plutonium or HEU for non-weapons purposes, provided, in the case of non-nuclear-weapon states, that it remains under safeguards.

[20] This apparent "breakout advantage" for the United States results from START II's requirement that Russia destroy its SS-18 missiles.

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The NPT is supplemented by a range of other accords and understandings. The International Atomic Energy Agency (IAEA), established in 1957, conducts agreed international monitoring of civilian nuclear facilities to ensure that bilateral supplier-recipient commitments and NPT commitments are being honored.[21] Various regional arrangements, such as Latin America's Treaty of Tlatelolco and the South Pacific's Treaty of Rarotonga, seek to keep those areas free of nuclear weapons.[22] The Nuclear Exporters Committee (Zangger Committee) and the Nuclear Suppliers Group (London Club), established in 1974 and 1975, respectively, provide their membership—industrial countries who strongly support the NPT—with forums to discuss policy problems and to coordinate export guidelines for technologies potentially related to nuclear weapons.

In recent years, a number of steps have been taken to strengthen the regime, partly in response to revelations concerning Iraq's extensive clandestine nuclear weapons program, which highlighted some serious weaknesses:

- Export controls in a number of important countries have been strengthened and the Nuclear Suppliers Group has tightened its export guidelines.
- The IAEA has moved to establish a capability to receive and respond to intelligence on nuclear developments provided by member states.
- The IAEA has begun to exercise its existing authority to carry out inspections at undeclared sites.
- The UN Security Council has identified the spread of weapons of mass destruction as a threat to international security, giving it the authority to act to counter proliferation.
- In cases ranging from North Korea to Iraq to Ukraine, the international community has demonstrated new unanimity and coordination in acting to counter the spread of nuclear weapons.

Despite these encouraging steps, several critical "threshold" states remain outside the regime (including Israel, India, and Pakistan). Moreover, two states —North Korea with its resistance to effective safeguards, and Ukraine with its ambivalence about giving up the nuclear weapons of the former Soviet Union still on its territory—pose urgent challenges to the regime. And a few other states may be attempting to pursue nuclear weapons programs, or helping others to do so, while remaining formally within the regime.

There are important linkages between the management and disposition of excess nuclear weapons and fissile materials and the future of the nonproliferation regime. As described in Chapters 4 and 5, some measures for managing excess military fissile materials in the United States and Russia could set a

[21] The European Community's EURATOM organization fills a similar role, in cooperation with the IAEA, in Western Europe.

[22] The Tlatelolco treaty also commits its parties to abide by an IAEA safeguards regime comparable to that in the NPT.

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standard for application to civilian materials elsewhere, strengthening safeguards and security for fissile materials worldwide.

In addition, as noted in Chapter 1, measures to demonstrate that thousands of nuclear weapons had been dismantled and the resulting fissile materials committed to exclusively nonexplosive purposes could, in concert with recent progress in arms reductions, help build support for an indefinite extension of the NPT at the 1995 extension conference, and for measures to strengthen the nonproliferation regime.

The Role of the IAEA

Efforts to stem the spread of nuclear weapons are critically dependent on the strength and credibility of the systems and organizations given the responsibility to carry them out, in particular the IAEA.

The IAEA's traditional approach to safeguards focused on verifying declared facilities at declared sites. Even though the IAEA has always had statutory authority to inspect other sites, support from its key members was not sufficient to enable it to do so. The discovery of a vast nuclear weapons program in Iraq, taking place largely at undeclared sites, clearly demonstrated that this approach was insufficient. This accelerated an IAEA reform effort that was already under way. The agency is now taking a variety of steps to strengthen its safeguards, including placing new emphasis on collecting and integrating information from all available sources on the nuclear programs of individual states, and reaffirming its right to conduct special inspections at undeclared sites. This reinvigoration must continue.

The IAEA has taken on an expanded role in recent years, and this study recommends new missions, particularly relating to storage and long-term disposition of fissile materials. These new roles will place new burdens on the agency, and successful implementation is likely to require continuing reform. Most of these missions involve political issues about which the IAEA's diverse membership would need to develop a workable consensus, and this will not come easily in some cases. Sustained diplomatic effort to build support for these new missions will be required.

Equally important, to maintain a strengthened safeguards effort, or to participate in monitoring fissile materials released from nuclear weapons programs, the IAEA will need greater resources. The current IAEA safeguards budget for the entire world is in the neighborhood of $68 million a year—an inadequate sum and a trivial one on the scale of security spending by the major powers.

Unfortunately, however, the major powers have for many years insisted on keeping the IAEA to an essentially flat budget; only in recent years have they agreed to any increases at all, and these have been small compared to the major new responsibilities the agency has taken on. Although some other agency activities are funded by voluntary contributions, safeguards are funded by fixed

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assessments, which are set so that the major powers pay most of the bill. These assessments can be changed only by a vote of the Board of Governors. Efforts to substantially increase the budget are subject to the usual politics of international institutions, including disputes over issues such as the status of Israel and South Africa, and the reluctance of some major powers to provide more safeguards funding if the result is more inspections in their own countries.[23] The Clinton administration's recent nonproliferation initiative recognizes this problem, pledging to "seek to ensure that the International Atomic Energy Agency has the resources needed to implement its vital safeguards responsibilities."[24] Gaining the substantial increases in resources that are needed is likely to require more flexible approaches to both inspection and funding. Some possible approaches are discussed in Chapter 5.

CIVILIAN PLUTONIUM PROGRAMS

Management and disposition of excess weapons plutonium will take place in a context in which large quantities of separated plutonium are being produced, stored, and used for civilian nuclear fuel as well.[25] Currently, excess stocks of separated civilian plutonium are building up in parallel with the excess stocks of weapons plutonium resulting from weapons dismantlement.

The basic elements of the civilian plutonium cycle are reprocessing, to separate plutonium from spent reactor fuel; fuel fabrication, to turn that plutonium into fresh reactor fuel; and recyclin g, the use of plutonium in reactors.

Recent IAEA estimates indicate that as of late 1992, some 86 tons of plutonium separated from civilian spent fuel was in storage worldwide.[26] Most of the reprocessing that produced this plutonium was done in plants in Great Britain, France, and Russia. The rate at which plutonium is being produced by reprocessing remains higher than the rate at which it is being used in reactors, resulting in growing excess stocks. The stock of unused plutonium in store is expected to increase to between 110 and 170 tons by the latter part of this decade

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[23] Traditionally, in order to avoid appearing to discriminate between developed nations and developing states, the IAEA has generally focused its safeguards effort on the locations handling the largest quantities of sensitive materials, rather than focusing special efforts on countries judged to be the greatest proliferation risks. As a result, more than half of the agency's safeguards budget is spent on inspections in Germany, Canada, and Japan. Thus, the major powers believe they are "oversafeguarded" already, and would be reluctant to provide additional funds for even more inspections on their own territory. More flexible approaches to safeguarding that would permit some reallocation of resources are now under discussion.

[24] White House Fact Sheet, "Nonproliferation and Export Control Policy," September 27, 1993. The statement also pledged to work "to strengthen the IAEA's ability to detect clandestine nuclear activities."

[25] An excellent source of information on civilian—and military—plutonium programs is David Albright, Frans Berkhout, and William Walker, *WorldInventory of Plutonium and Highly Enriched Uranium 1992* (London: Oxford University Press for SIPRI, 1993).

[26] See J.S. Finucane, "Summary: Advisory Group Meeting on Problems Concerning the Accumulation of Separated Plutonium," IAEA, Division of Nuclear Fuel Cycle and Waste Management, September 21, 1993. More than half of this accumulated plutonium belonged to Great Britain and Russia; while other reprocessing countries have decided to use plutonium in light-water reactors to reduce the buildup of excess stocks, neither of these countries has yet taken this route.

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or early in the next century, depending on the scale of reprocessing and plutonium use over the intervening period.[27]

An infrastructure of existing and planned civilian facilities thus exists to store many tons of plutonium, fabricate it into reactor fuel, and use it in reactors. These facilities, however, are already burdened with managing civilian plutonium; using them to handle excess military plutonium would require substantially expanding them or displacing the civilian plutonium in some way (see Chapter 6).

Today's civilian plutonium programs in the advanced industrial countries result from decisions made in the 1970s, when it was believed that energy demand would increase much more rapidly than it has, that nuclear power would supply a larger fraction of that energy than it has, and that resources of uranium were far more limited than they have since proved to be.[28] Thus, it was believed that for a secure energy future, it would be essential to move quite rapidly to a plutonium fuel cycle, in which reactors would turn uranium-238 (U-238, which accounts for more than 99 percent of natural uranium) into plutonium, which could be used as a fuel, thereby extending uranium reserves by as much as a factor of 1,000.[29] The means to do this was the "breeder" reactor—so-called because by turning U-238 into plutonium it would produce more fuel than it consumed—combined with reprocessing and reuse of the resulting plutonium.

With the slower than expected growth of nuclear power production and the discovery of large new resources of uranium, the economic justification for such a plutonium cycle has receded some decades into the future. Nonetheless, a number of countries are continuing to actively pursue plutonium fuel programs, in order to maintain a role in advanced nuclear technology, to help ensure long-term energy supplies, and to explore the possibility that reprocessing and recycling might help ease the difficulties of managing nuclear waste.

The inertia of long-standing programs, written into policies, national laws, and binding contracts, is also a major factor in sustaining these plutonium efforts. Reprocessing plants whose construction began in the 1970s or 1980s are only now being opened, and plutonium fuel fabrication facilities planned for many years are nearing completion or beginning construction. Similarly, although breeder reactors have encountered technical problems in several countries and their commercialization has been greatly delayed, several long-standing breeder reactor development programs continue. Long-planned programs to use plutonium fuel in existing light-water reactors (substituting a plutonium-uranium

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[27] Finucane, ibid. Albright et al. (op. cit.) provide roughly similar estimates.

[28] For a useful overview of these changes, see Leslie Dircks, IAEA Deputy Director-General, "Nuclear Fuel Recycling: The IAEA Perspective," speech, Tokyo, March 25, 1992.

[29] A factor of roughly 100 would come from the 100-fold greater abundance of U-238 compared to the U-235 consumed in most reactors today; an additional factor of roughly 10 might come from the possibility of mining uranium resources that it would not be economical to exploit if only the U-235 were going to be used, but might become economical if the U-238 were going to be used as well.

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mixed-oxide (MOX) fuel for part of the LEU fuel these reactors normally use) are going forward in several countries.

At the same time, proliferation concerns and the currently unfavorable economics of plutonium use have led some nations, notably the United States, to promote postponing or abandoning reprocessing and the plutonium fuel cycle in favor of direct disposal of spent fuel.[30] On September 27, 1993, the Clinton administration announced a nonproliferation initiative which makes clear that while the United States will not interfere with reprocessing in Japan and Europe, "the United States does not encourage the civil use of plutonium and, accordingly, does not itself engage in plutonium reprocessing for either nuclear power or nuclear explosive purposes." The initiative called for an exploration of "means to limit the stockpiling of plutonium from civil nuclear programs."[31] Nevertheless, the vision of a plutonium fuel cycle remains deeply held by many in Europe, Russia, and Japan.

Current plutonium programs involve a complex web of international relationships governing different parts of the fuel cycle. Belgium, for example, needs contracts from France, Switzerland, and Germany to sustain its MOX fabrication plant. Japan, Germany, and other countries depend on France to reprocess their spent fuel, and Britain expects to provide major reprocessing services when its new facility opens. Russia is seeking foreign investment to complete a MOX fabrication plant and a new reprocessing facility.

At least two of the major nations involved—Germany and Japan—are rethinking aspects of their plutonium programs. But the long-standing investments and commitments at stake, combined with the international contracts involved, will make major changes in policy difficult. Policy decisions on the disposition of excess weapons-grade plutonium will need to take these conditions into account. The civilian plutonium programs of the major countries are described in Appendix B.

SAFEGUARDS AND PHYSICAL SECURITY

International efforts to reduce the proliferation risks posed by plutonium and enriched uranium rest on two basic concepts: (1) **safeguards** (both national and international) are designed to *detect* any diversion of materials and enable a timely response, thereby contributing to the deterrence of such diversions; and (2) **security** (currently entirely national, rather than international) involves

[30] In April 1977 the Carter administration announced its decision "to defer indefinitely the commercial reprocessing and recycling of the plutonium produced in U.S. nuclear power programs" (*PresidentialDocuments—Jimmy Carter*, Vol. 13, no. 15, April 18, 1977). An influential analysis that provided part of the technical basis for that decision is Spurgeon M. Keeny, Jr., *Nuclear Power: Issues and Choices*, Report of the Nuclear Energy Policy Study Group (Cambridge, Mass.: Ballinger Publishing Company, 1977).

[31] White House Fact Sheet, "Nonproliferation and Export Control Policy," September 27, 1993.

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measures to *prevent* any theft of materials, through the use of barriers, guards, and the like.[32]

Standards for both safeguards and physical security vary widely. In the case of *national* safeguards, most nations possessing significant quantities of nuclear materials have some form of national system for material control and accounting, to keep track of the quantities, locations, uses, and movement of nuclear materials under their control. The quality of these systems varies dramatically, however. The non-Russian states of the former Soviet Union, for example, are now facing the need to set up such systems for the first time, in the midst of ongoing economic and political transformations.

Similarly, standards of accounting at particular facilities also vary. At bulk plutonium processing facilities, for example, small percentage uncertainties in accounting for large quantities of material have so far made it difficult to meet the standard of "timely detection" of diversion of a "significant quantity" of plutonium (defined by the IAEA as 8 kilograms, although weapons can be made with less).[33] Therefore *containment and surveillance*—efforts to ensure that fissile materials do not leave certain areas, or the facility as a whole, undetected—are also an important factor in both national and international safeguards.

International safeguards have somewhat different purposes and objectives. While national safeguards are designed primarily to detect theft of material from the control of the state on whose territory the facility operates, international safeguards are designed to detect diversion by the state itself. Thus, all of the information provided by the facility operator must be treated as potentially suspect and subject to verification. International safeguards work much as a bank audit does: the operator of the facility provides records on the beginning

[32] This division of "safeguards" and "security" into two distinct activities follows the IAEA usage. However, in other contexts, the word "safeguards" is sometimes used to include both material control and accounting, and physical security. That, for example, is how the term is used in most official discussions of U.S. national systems for security and material control and accounting. For a useful discussion of many of the issues raised in this section, see Paul Leventhal and Yonah Alexander, eds., *Preventing Nuclear Terrorism* (Lexington, Mass.: Lexington Books, 1987).

[33] The chief problem in achieving such timely detection is that traditional material accounting techniques involved balancing the input and output from a plant with its current inventory, and for economic reasons, the plant shutdown required to take a full inventory could be done only at relatively long intervals (such as six months or a year). Thus, it could take that long for any missing material to show up on the books; and a very large amount of material would have been processed during the prolonged inventory period, requiring extremely precise accounting to detect diversions as small as a few kilograms. New techniques have been developed to try to address this problem in recent years, however, using instruments to measure process inventories without shutting the plant down, or frequent comparison of the plant input to ensure that the amount of material in process is not changing in unexplained ways. Even these techniques, however, do not assure that the criterion of timely detection of diversion of 8 kilograms of plutonium could be met at a large facility through material accounting techniques alone. For discussions, see, for example, William Walker and Frans Berkhout, "Safeguards at Nuclear Bulk Handling Facilities," in J.B. Poole and R. Guthrie, eds., *Verification Report 1992* (London: Verification Technology Information Center, 1992); and Marvin Miller, "Are IAEA Safeguards on Plutonium Bulk-Handling Facilities Effective?" Nuclear Control Institute, August 1990. For a summary of the current strengths and weaknesses of the overall safeguards regime, see Lawrence Scheinman, *Assuring the Nuclear Non-Proliferation Safeguards System* (Washington, D.C.: The Atlantic Council, October 1992).

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and ending inventory for the period in question, and the flows of material in and out, and the inspector independently verifies some of this information, to detect possible falsification of the records. For items that can be counted individually (such as money in the case of bank audits or fuel rods in the case of safeguards), this approach is highly effective. As noted, however, measurement uncertainties render diversions of bulk materials more difficult to detect—making it very desirable to package and seal material in discrete units wherever possible.

The standards for international safeguards also vary widely. Non-nuclear-weapon states who are parties to the Non-Proliferation Treaty must open all their nuclear facilities to comprehensive safeguards administered by the IAEA—so-called full-scope safeguards. Nations that are not party to the NPT, such as India, Pakistan, and Israel, do not face comparable requirements, although as a result of arrangements with nuclear suppliers, some individual facilities in these countries are under safeguards.[34] Nuclear-weapon states under the NPT (the United States, Russia, Britain, France, and China) are not required to open *any* of their facilities to safeguards, although in "voluntary offer" agreements, they have made some facilities available for inspection. The United States, for example, has offered to permit safeguards at all of its civilian nuclear facilities. In practice, the IAEA does not expend its limited budget on safeguarding U.S. facilities, since there is little risk that a nation that already possesses thousands of nuclear weapons would divert additional nuclear material from its civilian nuclear fuel cycle. Russia, by contrast, has opened only a handful of facilities to IAEA safeguards, even in principle. British and French civilian facilities are covered under arrangements with EURATOM, and some facilities in those countries are also inspected by the IAEA.

Even when all important facilities are under IAEA safeguards, monitoring standards vary from facility to facility. Many types of facilities are only checked annually or once every several months: thus, "timely detection" of a diversion would be difficult to achieve. Table 2-1 shows the types of facilities under IAEA safeguards at the end of 1992.

Standards of security for nuclear materials also vary widely. Unlike safeguards, where the IAEA has been given a major role, the IAEA's member states regard security for nuclear materials—often referred to as "physical protection"—as a matter of national sovereignty. Thus, although an attempt to set international standards was made in the 1980 Convention on the Physical Protection of Nuclear Material, that convention is quite vague in its requirements, applies primarily to international transport of materials, and has no provisions for verification or enforcement. Similarly, although the IAEA has published somewhat more detailed guidelines for physical protection of nuclear

[34] The members of the Nuclear Suppliers Group have long required safeguards on the facilities to which they export materials. In the spring of 1993, the Nuclear Suppliers Group agreed to make full-scope safeguards a condition of export of "major nuclear items."

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materials, these are purely advisory.[35] Neither the IAEA nor any other organization monitors or compiles information on physical security procedures worldwide.

TABLE 2-1 Facilities Under Safeguards or Containing Safeguarded Materials at the End of 1992

	Number of Facilities (number of installations)			
Facility Category	Non-Nuclear-Weapon States	Non-NPT States	Nuclear-Weapon States	Total
Power reactors	151 (182)	13 (17)	2 (2)	166 (201)
Research reactors and critical assemblies	134 (145)	22 (22)	2 (2)	158 (169)
Conversion plants	6 (7)	3 (3)	0 (0)	9 (10)
Fuel fabrication	33 (34)	9 (9)	1 (1)	43 (44)
Reprocessing plants	5 (5)	1 (1)	0 (0)	6 (6)
Enrichment plants	5 (5)	1 (1)	1 (1)	7 (7)
Separate storage facilities	35 (36)	6 (6)	5 (5)	46 (47)
Other facilities	54 (57)	4 (4)	0 (0)	58 (61)
Subtotal	423 (471)	59 (63)	11 (11)	493 (545)
Other locations	290 (468)	28 (32)	0 (0)	318 (500)
Nonnuclear installations	0 (0)	3 (3)	0 (0)	3 (3)
Total	713 (939)	90 (98)	11 (11)	814 (1048)

NOTE: The first category includes states with IAEA Information Circular (INFCIRC) 153 agreements, which refers to comprehensive safeguards agreements pursuant to the Treaty on the Non-Proliferation of Nuclear Weapons and the Treaty of Tlatelolco (excludes locations in Iraq). The second category includes INFCIRC/66/Rev. 2 agreements covering specific facilities in non-NPT states and Taiwan.
SOURCE: T.E. Shea and K. Chitumbo, "Safeguarding Sensitive Nuclear Materials: Reinforced Approaches," *IAEA Bulletin*, Vol. 35, no. 3, 1993, p. 26.

[35] See IAEA, Information Circular (INFCIRC) 274, "The Convention on the Physical Protection of Nuclear Material," May 1980; INFCIRC 225, Revision 2, "The Physical Protection of Nuclear Material," December 1989 (the IAEA's advisory guidelines); and INFCIRC 254, "Communications Received from Certain Member States Regarding Guidelines for the Export of Nuclear Material, Equipment, or Technology," February 1978 (export guidelines including physical protection).

Typically, though not always, security for Category I materials—those containing significant quantities of unirradiated plutonium or HEU—would include storing the material in a locked vault, in an area that was guarded, and to which access was carefully controlled. All personnel entering or leaving would be searched. The

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Different countries have very different views of the types of likely threat, of the best means to respond to it, and of how much to spend on security. In Russia, major nuclear material facilities are generally under heavy armed guard, but techniques for detailed accounting of the material have received less emphasis, in part because during the Soviet era, the most likely threat was long seen as an outside attack rather than an insider diversion. In Japan, by contrast, since the government believes that the unity of Japanese society makes outside attack unlikely, the guards at plutonium stores and other nuclear facilities do not carry firearms. But the technologies in place in Japan for safeguards and material accounting are some of the best in the world.[36]

Unfortunately, as with all human endeavors, the effectiveness of physical security systems is often considerably less in practice than it is on paper. For example, even in the U.S. nuclear weapons complex, probably among the most secure facilities in the world, tests held as recently as the mid-1980s determined that plausible terrorist attacks could succeed in stealing significant quantities of plutonium, or even bomb components. A large-scale effort was then launched to identify weaknesses in the system and make corrections.[37]

Safeguards and security for plutonium in spent fuel are less stringent than those for separated plutonium and HEU. In general, it is assumed that the intense radioactivity of spent fuel, and the size and weight of spent fuel bundles or casks, would reduce the risk of theft to almost zero. Since states with significant nuclear programs generally have spent fuel on their territories, only states without significant nuclear programs or subnational groups would pose plausible threats to steal spent fuel. Neither the Convention on the Physical Protection of Nuclear Materials nor IAEA recommendations require much more for such materials than placing them within a fenced area to which access is controlled.

In most countries, spent fuel is initially stored in water-filled ponds at reactor sites. The security applied to this fuel is often simply the same security applied to protect the reactor itself from sabotage.[38] At many sites, these ponds are nearing their capacity, and a number of countries are therefore considering

guarded area around the vault (known as the "inner area") would be surrounded by a larger area somewhat less carefully controlled, known as the "protected area." Fences or similar barriers would surround both areas, and guards would be in communication with forces that could respond to an attempt to attack the facility.

[36] Useful descriptions of physical security philosophies in a number of countries, including Japan, can be found in a special issue of the *Journal of Nuclear Materials Management*, January 1988. For a description of the Russian approach, see Oleg Bukharin, *The Threatof Nuclear Terrorism and the Physical Security of Nuclear Installationsand Materials in the Former Soviet Union* (Monterey, Calif.: Center for Russian and Eurasian Studies, Monterey Institute of International Studies, Occasional Paper No. 2, August 1992).

[37] House of Representatives, Energy and Commerce Subcommittee on Oversight and Investigations, *Adequacy of Safeguards and Securityat Department of Energy Nuclear Weapons Production Facilities*, March 6, 1986. See also National Research Council, *Material Control andAccounting in the Department of Energy's Nuclear Fuel Complex* (Washington, D.C.: National Academy Press, 1989), pp. 29-31.

[38] In the United States, for example, the "design basis threat" against which security systems for reactors and spent fuel ponds are designed includes the possibility of an armed attack by a small group of well-trained and dedicated individuals, with the cooperation of one insider. Standards in a number of other countries are reportedly lower. See *U.S. Codeof Federal Regulations*, Part 10, Section 73, January 1, 1993.

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or implementing dry cask storage, sometimes at away-from-reactor sites. The security included in these concepts is often minimal. In the United States, for example, the staff of the Nuclear Regulatory Commission has proposed draft regulations that would require little more than a fence and two unarmed watchmen on duty at any time.[39]

Similarly, ongoing international discussions of safeguards and security that might be imposed to limit the risk of diversion of spent fuel from underground repositories have not yet reached any conclusion. Feasible technical approaches for low-cost monitoring of such sites are available, such as the use of remotely operated seismic stations to detect drilling operations in the vicinity of the repository.

In summary, current standards for safeguards and physical protection for civilian plutonium vary widely, and are considerably less stringent than those applied to nuclear weapons and plutonium in military stocks. Varying and lower standards may be justified in the case of spent fuel for the first decades outside the reactor, when its high radioactivity makes it difficult to steal or divert, but they are not justified in the case of separated civilian plutonium or HEU. Discussions of specific measures for improving safeguards and security for nuclear materials, building on the steps that should be taken with excess plutonium from dismantled weapons, can be found in Chapters 4 and 5.

[39] See U.S. Nuclear Regulatory Commission, "Interim Licensing Criteria for the Evaluation of Physical Protection Plans for Certain Storage of Spent Fuel," Preliminary Staff Position, October 20, 1992.

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3

Criteria for Comparing Management and Disposition Options

The primary goal in the management and disposition of excess weapons plutonium should be to minimize the risks to national and international security posed by the existence of this material. Accordingly, the discussion of criteria for comparing the possible approaches in this report begins with these security risks. The issues of timing and capacity—how quickly an approach can be put into operation and how rapidly it can process weapons plutonium thereafter—are tightly intertwined with other aspects of security, and these matters are treated together here. The report then turns to criteria related to economics; environment, health, and safety; and other policies and objectives.

This presentation of criteria aims to be comprehensive, as a guide for further analyses. The constraints of this study, however, did not permit applying them with the same rigor described below; instead, in developing its recommendations, the committee has applied these criteria in more general terms.

CRITERIA RELATED TO SECURITY, TIMING, AND CAPACITY

As described in Chapter 1, the goal of minimizing security risks from excess weapons plutonium can be divided into three objectives:

1. to minimize the risk that either weapons or fissile materials could be obtained by unauthorized parties;

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2. to minimize the risk that weapons or fissile materials could be reintroduced into the arsenals from which they came, thereby halting or reversing the arms reduction process; and
3. to strengthen the national and international control mechanisms and incentives designed to ensure continued arms reductions and prevent the spread of nuclear weapons.

The preceding chapters have described these risks. The relative importance of the various risks may change substantially over time, in ways that are difficult to predict in some cases.

U.S. consideration of the risks associated with the various options for management and disposition of its own plutonium must be informed by an awareness of the potential linkages between U.S. choices and the choices that may be made in the former Soviet Union. U.S. policy could affect the management and disposition of excess weapons plutonium in the former Soviet Union in a variety of ways—ranging from simply setting an example on the one hand, to financial assistance, negotiated agreements to pursue particular approaches, or outright purchase of former Soviet weapons plutonium on the other. Moreover, what is done with excess weapons plutonium in the United States and the former Soviet Union could affect, for good or ill, the fate of the substantially larger (and still growing) quantities of separated and unseparated plutonium discharged from civilian nuclear power reactors worldwide.

Characterizing the Risks

Candidate disposition approaches typically consist of several steps, beginning with intact nuclear weapons and proceeding through dismantlement and intermediate storage to long-term disposition.[1] Long-term disposition itself is likely to involve some number of intermediate processing, storage, and transport steps, ending with either the physical destruction of the plutonium (by fission or transmutation) or its disposal in a form and location where it is intended to remain indefinitely.[2] Evaluating the security benefits and liabilities of each approach requires an assessment of each step within it, with respect to each type of opportunity or threat.

The risks of theft and breakout differ greatly in their urgency and characteristics. As noted in Chapter 2, the risk of theft of fissile materials in the former Soviet Union is serious and urgent, given the political, social, and economic turmoil there. Theft of as little as several kilograms of material could pose major security risks.

[1] Not all excess weapons plutonium will begin in the form of intact nuclear weapons, however; there are substantial quantities in scrap and residues in the nuclear weapons complexes today.

[2] Or, to be more specific, until it decays radioactively (with a half-life of 24,000 years) to uranium-235 (U-235)—also a potential weapons material, with a half-life of 700 million years.

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By contrast, any breakout effort large enough to affect the strategic balance would require the use of much larger quantities of fissile material (in order to make thousands of weapons, rather than just a few). However, any barriers to inhibit either the United States or Russia from a major breakout could only increase the time, cost, observability, and political inconvenience (such as that arising from having to abrogate agreements) involved in doing so. The United States or Russia could, at any time it chose, either recover plutonium from nearly any form and location on its territory where it might exist, or produce new plutonium or highly enriched uranium (HEU). Those potential proliferators who lack the technology and knowledge associated with a large nuclear weapons complex or an advanced civilian nuclear program would not have as many options.

The risks of theft or diversion associated with a particular step in this process depend on four classes of factors:

1. *The state of the plutonium*, including:

a) its chemical form (for example, plutonium metal, oxide, carbide, or nitrate, of which metal is most convenient);
b) its isotopic composition (the fraction of plutonium-239 (Pu-239), the most attractive isotope for bomb making, versus the fractions of Pu-240, Pu-241, Pu-242, and Pu-238);
c) any admixture of impurities (such as other metals, oxides, or carbides; fission products; or other neutron absorbers, which, variously, affect chemical processing requirements and radiological hazard to bomb-makers); and
d) its configuration (for example, part of an assembled warhead, intact pit, deformed pit, ingot, powder, ingredient of fuel element).

2. *Stockpiles and transportation risks*, namely:

a) inventories or annual throughputs (as appropriate) of the various facilities storing or handling plutonium;
b) the amount of time the inventories remain in the step in question and the duration of the throughputs; and
c) the number of times plutonium is transported from place to place (when the barriers, described below, are likely to be smaller), and the distance and duration of these trips.

3. *Barriers to the theft or diversion*, namely:

a) barriers inherent in the form of the material (for example, dilution, measured by the percentage of plutonium in the mixture, and gamma radiation dose, measured in roentgen-equivalent-man (rem) per hour at a specified time and distance);
b) engineered barriers (for example, massive containers, vaults, buildings, fences, special transport vehicles, detectors, alarms);

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c) geographic and geologic barriers (for example, site isolation, difficult terrain, burial depth, difficulty of excavation and tunneling); and
d) institutional barriers (for example, proximity and capability of guard forces, intensity and reliability of monitoring).

4. *Characteristics of the threat*, including:

a) potential complicity of the custodial organization or of individuals within it;
b) capabilities of attacking forces (numbers, weapons, training, organization, determination) in the case of forcible theft; and
c) knowledge, skills, money, technology, and organization available to the prospective bomb-makers.

The foregoing considerations suggest a matrix approach to characterizing the security implications of different options for the disposition of weapons plutonium, in which the rows of the matrix are the steps in a particular option, and the columns portray:

i. qualitative assessments of the attractiveness of the plutonium as a raw material for weapons, considering factors 1a-d, above;
ii. numerical measures of quantity, time, and dilution (factors 2a-c, and 3a); and
iii. qualitative evaluations of vulnerability as governed by the interaction of barriers (3a-d) with threat characteristics (4a-c) for the main classes of threats.

This procedure is illustrated in Table 3-1, which outlines how it would be applied to the conversion of weapons plutonium into spent light-water reactor (LWR) fuel. The tabulation lists the 10 steps involved, together with the date when each would begin. This would be followed by an assessment of each step with regard to three characteristics:

Attractiveness. Assessing the attractiveness of plutonium in particular forms to prospective bomb-makers is, inherently, a complex and potentially contentious undertaking, involving the assignment of weights to the various relevant characteristics. Indeed, attractiveness is likely to depend not only on the characteristics of the plutonium but on those of the bomb-makers, which means that, in principle, different attractiveness levels might correspond to different classes of threat. In particular, one significant component of the risk of theft is likely to be theft by parties who do not have the capability to process the material or fabricate it into weapons, for sale to those who do. Forms of plutonium that would be quite difficult for unsophisticated parties to remove, store, and transport—such as those emitting intense radioactivity—are likely to pose major obstacles to this form of theft, even if they would pose significantly smaller barriers to parties with the sophistication required to fashion a nuclear weapon.

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TABLE 3-1 Format for Characterizing Security Risks of a Disposition Approach

Approach: Starting from storage as pits, perform once-through irradiation of weapons plutonium in mixed-oxide fuel in a light-water reactor, followed by storage and eventual emplacement as spent fuel in a geologic repository

Step (and start date)	Attractiveness of Pu at this step, in		Quantitative Factors				Vulnerability (based on threat barrier interactions) with respect to threat of		
	Initial Form	Final Form	Inventory or through-Put (kg Pu or kg Pu/year)	Residence Time or Duration (years)	Dilution (kg of material per kg Pu)	Gamma Dose, Distance[a] (rem/hm)	Covert Diversion	Forcible Theft	Covert Theft
Storage as pits (1994)									
Conversion to oxide (1998)									
Transport as oxide (1998)									
Fabrication to MOX (1999)									
Transport as MOX (1999)									
Storage as MOX (1999)									
Burnup in LWR (2000)									
Spent fuel storage (2001)									
Spent fuel transport (2015)									
Repository disposal (2015)									

NOTE: Table is intended for illustrative purposes only; ratings are intentionally left blank. Start dates assigned to the various steps are also purely illustrative.

[a]Time of dose measurement is start of step unless otherwise indicated.

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Quantitative Factors. The first two columns under "quantitative factors" in the security risk matrix (inventory or throughput, and average time in the step or duration of the step) are indices for which higher numbers mean higher risks, while the third and fourth columns, dilution and gamma dose, are indices for which higher numbers mean lower risks. For storage steps, the product of inventory and average residence time (equivalent to the integral under a quantity-versus-time curve) is a particularly informative quantitative index of risk at given attractiveness and vulnerability levels.

Vulnerability. The characterization of vulnerability here is based on three reference classes of threat: covert diversion by the state controlling the facility, forcible theft, and covert theft. Vulnerability at each step to each of these threats would probably be best characterized simply as "low," "medium," or "high," based on judgments about the effectiveness of the relevant barriers against the indicated threats. Any more discriminating characterization than this probably would not be warranted in light of the uncertainties associated with threats and barriers alike.[3]

Since, in many cases, the plutonium leaves a step in a form different from that in which it entered, a tabulation such as Table 3-1 should show both initial and final attractiveness levels for each step.

Table 3-2 shows the five-level "attractiveness" classification specified in the relevant U.S. Department of Energy (DOE) order,[4] which could be used to fill out the "attractiveness" columns of Table 3-1, although it does not distinguish among the different types of threat described above. As the table shows, assembled weapons are considered to be the most attractive items for theft or diversion, and are always in the top safeguards category (meaning the most care required in security and accounting). Relatively pure plutonium or HEU is judged to be one step less attractive, but still should be treated as being in the top safeguards category, even in amounts somewhat smaller than those needed to produce a weapon. Other materials require progressively lower levels of protection.

Table 3-3 shows some of the relevant characteristics of different forms of plutonium, ranging from intact pits at the top of the table to various forms of spent fuel or high-level waste (HLW) glass at the bottom. Characteristics listed include such factors as the size and weight of the item in question (which help determine how easy it is to steal), the radioactivity (which helps determine both

[3] It is not useful to specify vulnerability levels for over diversion in this format, because (i) as long as the plutonium remains on the territory of the state from whose weapons it came, that state will have the resources to overcome virtually any barriers if it chooses to do so (as noted above), meaning that the vulnerability can be simply characterized as more or less proportional to the attractiveness level; and (ii) if the plutonium is *not* on the territory of the original possessor state, the category of "overt diversion" is not really meaningful. The options available to the original possessor state in the latter instance amount to forcible theft and covert theft, the vulnerability to which is characterized.

[4] See U.S. Department of Energy, Order 5633.3A, "Control and Accountability of Nuclear Materials," February 12, 1993.

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TABLE 3-2 Attractiveness Levels and Safeguards Categories from DOE Order 5633.31

Type of Material	Attractiveness Level	Safeguards Category (I = greatest concern) Versus Quantity of Contained Material (kg)							
		Pu or U-233				U-235			
		I	II	III	IV	I	II	III	IV
Weapons[a]	A	Any quantity is Category I				Any quantity is Category I			
Pure Products[b]	B	>2	0.4-2	0.2-0.4	<0.2	>5	1-5	0.4-1	<0.4
High-grade materials[c]	C	>6	2-6	0.4-2	<0.4	>20	6-20	2-6	<2
Low-grade materials[d]	D	NA	>16	3-16	<3	NA	>50	8-50	<8
All other materials[e]	E	any reportable quantity is Category IV				any reportable quantity is Category IV			

NOTE: Reportable quantities are 1 g of Pu-239 to Pu-242 and enriched uranium, 0.1 g of Pu-238, NA = not applicable.

[a]Assessembled weapons and test devices.

[b]Pits, major components, buttons, ingots, recastable metal, directly convertible materials.

[c]Carbides, oxides, solutions of >25 g/L, nitrates, etc., fuel elements and assemblies, alloys and mixtures, UF_4 or UF_6 at 50% or more enrichment.

[d]Solutions of 1-25 g/L, process residues requiring extensive reprocessing, moderately irradiated material, Pu-238 (except in waste), UF_4 or UF_6 at 20-50% enrichment.

[e]Highly irradiated forms, solutions of <1 g/L, uranium in any form and quantity containing greater than 20% U-235.

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TABLE 3-3 Some Security-Related Characteristics of Plutonium in Different Forms

Form	Mass per Item (kg)	Max. Item Dim. (cm)	Pu per Item (kg)	Pu Conc. (kg/kg)	Gamma Dose Rate (rem/h) at Surface	Gamma Dose Rate (rem/h) at 1 Meter
Intact pit (WPu metal)	ca. 4	ca. 10	ca. 4	1	0.8	0.002
RPu metal sphere, δ-phase	6	9	6	1	17	0.03
PuO_2 powder, WPu	(powder @ 1 g/cm^3)			0.88	1	0.009
Same, RPu	(powder @ 1 g/cm^3)			0.88	20	0.2
MOX fuel pellet, WPu	0.006	1	3×10^{-4}	0.05	0.05	1×10^{-6}
Same, RPu	0.006	1	3×10^{-4}	0.05	1	2×10^{-5}
MOX fuel rod, WPu	2.5	410	0.1	0.04	0.03	1.4×10^{-4}
Same, RPu	2.5	410	0.1	0.04	0.7	3×10^{-3}
MOX fuel assembly, WPu	658	410	25	0.038	0.03	3×10^{-3}
Same, RPu	658	410	25	0.038	0.7	0.06
MHTGR WPu fuel block	100	80	0.8	0.008	0.5	0.02
Irradiated MOX fuel assembly, WPu						
0.4 MWd/kgHM, 2 years	658	410	23	0.035	50,000	4,500
10 years	658	410	23	0.035	440	40
30 years	658	410	23	0.035	190	17
100 years	658	410	23	0.035	37	3
40 MWd/kgHM, 10 years	658	410	18	0.027	4,4000	4,000
30 years	658	410	18	0.027	20,000	1,800
100 years	658	410	18	0.027	4,000	360
50 MWd/kgHM, 10 years	658	410	9	0.014	55,000	5,000
30 years	658	410	9	0.014	25,000	2,300
100 years	658	410	9	0.014	5,100	460
Borosilicate glass log with WPu and high-level wastes						
Small, 2% Pu, 20% HLW	250	50	4	0.02	not calculated	
Large, 2% Pu, 20% HLW	2,200	300	34	0.02	5,000	900
Same, + 10 years	2,200	300	34	0.02	4,000	720
Same, + 30 years	2,200	300	34	0.02	2,500	450
Same, + 100 years	2,200	300	34	0.02	500	90

NOTE: Max. = maximum, dim. = dimension, conc. = concentration; WPu = weapons plutonium, assumed to contain 0.2 weight percent americium-241 (from initial 0.4% Pu-241, aged 14 years); RPu = reactor plutonium, assumed to contain 4 weight percent americium-241 (from initial 9% Pu-241, aged 12 years); δ-phase = delta-phase, one of the six crystalline phases in which plutonium occurs (the two most commonly mentioned in connection with nuclear weapons are alpha phase (density 19.6 g/cm^3) and delta phase (density 15.7 g/cm^3)); MOX = mixed-oxide; MHTGR = modular high-temperature gas-cooled reactor; MWd/kgHM = megawatt-days (of thermal energy output) per kilogram of heavy metal; HLW = high-level waste. All characteristics for intact pits are for illustrative purposes only; actual dimensions are classified.

Detailed notes for this table can be found in *Management and Disposition of Excess Weapons Plutonium: Report of the Panel on Reactor-Related Options* (Washington D.C.: National Academy Press, 1994).

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Management and Disposition of Excess Weapons Plutonium

the ease of theft or diversion and the difficulty of separating the plutonium), and the like.

The foregoing discussion addresses the risk of theft and breakout, but the risks and opportunities of a particular management and disposition approach with respect to the third category of security issues (influences on efforts to reduce nuclear arsenals and stem the spread of nuclear weapons) are more dependent on political perceptions and thus inherently more difficult to characterize. These risks and opportunities will depend in part on:

1. *Timing*, that is, the speed with which various steps (such as dismantlement of weapons, implementation of safeguards over excess fissile materials, and long-term disposition of fissile materials) can be accomplished. This includes the relation of these steps to the timing of other relevant international events, such as Ukrainian nuclear weapons decision making and the April 1995 NPT extension conference.
2. *Transparency*, that is, the degree to which it can be demonstrated to relevant members of the international community (including Russia, the United States, the other former Soviet states with nuclear weapons on their soil, other declared and undeclared nuclear-weapon states, and non-nuclear-weapon states) that steps that have been announced, ranging from retirement of deployed weapons through dismantlement, storage, and long-term disposition, are in fact being carried out.
3. *Constraints*, that is, the degree to which states such as the United States and Russia accept limits on their nuclear weapons capabilities that would be difficult and costly to reverse (thus strengthening the arms reduction regime and demonstrating their compliance with the NPT requirement for negotiating in good faith toward disarmament) and that parallel in some respects the constraints imposed on other countries in the name of nonproliferation (thus reducing the discrimination inherent in the nonproliferation regime and improving prospects for approval of an indefinite or long-term extension of the NPT and strengthened safeguards).

The relation of these issues to a reductions and transparency regime for nuclear weapons and fissile materials is discussed in more detail in Chapter 4.

Standards

Characterizing the security risks of the various disposition options in the ways just described will provide insight into the areas of greatest risk within each option and a basis for comparing overall risk among options. These comparisons will inevitably be judgmental because they involve different attributes and classes of risk and opportunity, many of which can only be characterized in a general way. There is no defensible way to compute a single quantitative index of overall risk for each option; doing so would require agreeing on numerical values and relative weights for each relevant characteristic and threat.

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Within the constraints of this study, the committee was unable to pursue the approach just described for each of the options considered. That task should be pursued in subsequent analyses.

To be most useful, however, criteria should not only provide a basis for relative comparisons among options, but also provide guidance as to "How good is good enough?" As outlined in Chapter 1, two clear standards for managing the stages of this process should be set: the *stored weapons standard*, meaning that to the extent possible, the high standards of security and accounting applied to storage of intact nuclear weapons should be maintained for these materials throughout dismantlement, intermediate storage, and long-term disposition; and the *spent fuel standard*, meaning that options for the long-term disposition of weapons plutonium should seek to make this plutonium roughly as inaccessible for weapons use as the much larger and growing stock of plutonium in civilian spent fuel. Further steps should be contemplated, however, to move beyond the spent fuel standard and reduce the security risks posed by *all* of the world's plutonium stocks, military and civilian, separated and unseparated; the need for such steps exists already, and will increase with time.

More specific criteria related to technical options for storage are described and discussed in Chapter 5, while a set of criteria relevant to long-term disposition—including minimizing the time required for disposition, minimizing the risks of theft or diversion in the various steps involved, and minimizing the risks of recovery of the plutonium in its final form—are addressed in Chapter 6.

CRITERIA AND ISSUES IN ECONOMIC EVALUATION OF ALTERNATIVES

The monetary costs (or benefits) of alternative approaches to the management and disposition of weapons plutonium are of secondary importance compared to the security aspects. The security risks associated with this material are so great that it is difficult to imagine choosing an approach that was significantly riskier than another because it would save money—all the more so because the total sums involved are unlikely to be nearly as large as those that the United States and the former Soviet Union routinely invested in the past in attempts to buy security against nuclear weapon dangers.

Nevertheless, the economic dimension of alternative disposition approaches should be examined to assist in ranking approaches that are not readily distinguishable on security grounds, to facilitate planning for the investments that will be required for the approach chosen, and to correct some of the misimpressions put forward in recent years concerning the economic merits of the various approaches.

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Principles and Pitfalls in Cost Comparisons

Comparison of the economics of alternative approaches requires that the costs and revenues be estimated on a consistent basis. Such calculations can be quite complex, and the range of conventions and assumptions routinely used in carrying them out is wide. Relevant factors include:

1. the treatment of inflation;
2. whether the activities are carried out by government or civilian entities, or a combination, and corresponding assumptions about the real cost of money appropriate for the entities operating them, and property taxes and insurance costs associated with the facilities and operations;
3. conventions and assumptions relating to the components of the capital investments associated with the activities, including

a) the relevant costs of land, materials, labor, and purchased components in the region where the approach will be implemented;
b) the inclusion of indirect as well as direct costs;
c) the size of the "contingency" factor allowing for growth in construction costs beyond the baseline estimate;
d) the inclusion or exclusion of interest on investments made before the operational phase commences (often termed "interest during construction," although in principle the category is broader);

4. the degree of comprehensiveness, including costs of all the facilities and operations needed to perform the relevant mission;
5. the means by which subsidiary benefits of plutonium disposition operations (such as the generation of electricity) are taken into account in the economic calculations;
6. the treatment of "sunk" costs in relevant facilities and operations, that is, costs incurred prior to the current consideration of the possible use of particular facilities and operations for the management and disposition of weapons plutonium; and
7. the operational lifetime of the facilities (or, in some cases, the period over which the investment in them is to be written off).

Variations and inconsistencies in the treatment of these factors make it practically impossible to derive informative conclusions about costs of alternatives from direct comparison of final cost estimates obtained in different studies of the individual disposition approaches; rather, it is necessary to reconstruct a consistently based set of estimates starting from the building blocks (such as estimates of direct construction costs, or of labor and materials requirements) that such studies provide.[5]

For projects extending over several decades, consistent assumptions concerning the rate of inflation and the real cost of money are particularly important.

[5] Studies that offer estimates of costs without providing sufficient detail about the derivation of these to permit such reconstruction are not useful for purposes of making systematic comparisons.

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These factors can be crucial in determining whether a given project will appear to be a money-maker or a money-loser. An inflation figure of roughly 3 percent is reasonable, based on recent experience and current projections. The Office of Management and Budget (OMB) specifies that evaluations of federal projects with benefits in the private sector should use a real cost of money of 7 percent;[6] the latter figure was chosen by OMB as typical of real rates of return in the private sector, and therefore its use helps to limit the possibility of the government competing with the private sector with the unfair advantage of borrowing at substantially lower rates.[7]

A second key issue is the degree of comprehensiveness and realism in the estimates of capital and operating costs. All of the important elements must be included, on a comparable basis, for all of the options. The degree of optimism or realism in diverse cost estimates must also be comparable. We note that the available studies do not always meet these criteria, and we found it difficult to determine, from the available information, how large the distortions resulting from the differences in comprehensiveness and realism might be.[8]

The treatment of the costs of any required conversion of plutonium from weapons components—"pits"—to oxide or other forms that might be required by particular disposition approaches must be consistent. In recent studies of reactor options, for example, some have included this cost, and some have assumed that the government would provide plutonium oxide without charge. Because not all approaches require conversion to oxide, a fair economic comparison of all of the possibilities demands that those approaches requiring this conversion should be assigned the costs of it.

Perhaps the most fundamental conceptual issues in the economic evaluation of approaches to the management and disposition of weapons plutonium arise in determining which costs and revenues should be counted as part of this mission, and which should not. In general, if a facility already exists and the

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[6] Office of Management and Budget, "Benefit-Cost Analysis of Federal Programs: Guidelines and Discounts," OMB Circular A-94, October 29, 1992.

[7] In DOE's *Plutonium Disposition Study*, for example, government construction of advanced reactors to consume weapons plutonium was found to make a substantial profit for the government, in large part because the assumed low real cost of money (4 percent per year) provided a substantial competitive advantage against private electric power plants financed at much higher costs of money. The 4 percent figure is defensible as the cost of money to the government based on prevailing government bond yields (running at 7-8 percent) and inflation (past and projected, running at 2.5 to 3.5 percent), but it directly contradicts the OMB guidance. DOE's sensitivity analysis indicates that if the other assumptions in study were held constant and the cost of money was raised to 7 percent, the analyzed operations would involve substantial net costs to the government, rather than net profits. U.S. Department of Energy, Office of Nuclear Energy, *Plutonium Disposition Study*, 2 Vols. (Washington, D.C.: U.S. Department of Energy, July 2, 1993).

[8] DOE's *Plutonium Disposition Study* (ibid.), for example, notes considerable variations in comprehensiveness among the various vendor reports provided to DOE's Technical Review Committee. Moreover, as DOE's Peer Review Group noted, these vendor reports are excessively optimistic with respect to costs and schedules, and it is difficult to determine whether there are substantial variations in the degree of optimism among the different options. See R.S. Brodsky, D. Okrent, F.P. Baranowksi, P.J. Turinsky, and T.L. Neff, *Peer Review Report, U.S. Departmentof Energy Plutonium Disposition Study*, Office of Nuclear Energy (Washington, D.C.: U.S. Department of Energy, June 30, 1993).

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activity would take place regardless of whether excess weapons or weapons plutonium were involved, only the *net additional* costs and revenues directly associated with management and disposition of excess nuclear weapons and plutonium should be counted toward this mission. If, for example, weapons plutonium were to be used as fuel in existing light-water reactors, the revenues those reactors produce would be the same as if they had produced the same quantities of electricity while continuing to use low-enriched uranium fuel (and therefore none of those revenues can be attributed to the plutonium disposition mission); the costs (or benefits) attributable to plutonium disposition are the net additional costs (or savings) of using plutonium rather than uranium as fuel in these reactors.

At the other extreme, if a new facility is built exclusively to handle weapons plutonium, its total cost must be counted. If a new facility is built to handle weapons plutonium and produces some other needed product or service as well (such as a reactor built for plutonium disposition that also produces electricity), the cost or benefit attributed to the plutonium disposition mission should be the total cost associated with the facility *minus* the costs associated with producing that product or service in the way in which it otherwise would have been produced. The cost attributable to the plutonium, in other words, is the additional cost of producing the given product or service in a way that also accomplishes the plutonium disposition mission, compared to producing it by other means.

More generally, one can distinguish four types of situations, according to whether: (a) the facilities are preexisting or new, and (b) their use in the plutonium disposition mission will be single-purpose or multipurpose. The box on p. 74 provides a matrix illustrating this categorization and these prescriptions for the costs attributable to management and disposition of excess weapons plutonium in the various possible situations. A given program for the several stages of this process will often be made up, of course, of a variety of activities falling into more than one of the above categories, requiring particular care in matching the appropriate costing conventions to different parts of the project. Given the resource constraints of this study and the wide variations in assumptions, comprehensiveness, and realism in the studies available to guide its work, the committee has not attempted detailed cost estimates of any but a few of the available options, confining itself instead to outlining the general principles to be applied, and to rough judgments of the relative cost of different approaches.[9]

[9] Specific cost estimates for the reactor and vitrification options can be found in *Management and Disposition of Excess Weapons Plutonium:Report of the Panel on Reactor-Related Options* (Washington D.C.: National Academy Press, 1994).

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ASSIGNING COSTS OF PLUTONIUM MANAGEMENT AND DISPOSITION

TABLE 3-4 Cost Estimation Categorization of Plutonium Management and Disposition Facilities and Uses

	Preexisting Facilities	New Facilities
Single-purpose use	"Igloos" at Pantex weapons assembly and disassembly facility, used for storage of weapons plutonium	Dedicated (non-electricity-producing) plutonium-burning reactor designed for this purpose
Multipurpose use	Existing commercial reactor using mixed-oxide fuel to process weapons plutonium and generate electricity	Advanced reactor constructed at government site for weapons plutonium processing and electricity generation

Single-Purpose Use of New Facilities: In this simplest case, new facilities are constructed and operated for no purpose other than the management and disposition of weapons plutonium, and no marketable products or other quantifiable economic benefits to society besides the disposition of the weapons plutonium result. In such situations, all of the capital charges and operating costs clearly are assignable to the plutonium disposition mission, and there are no offsetting revenues or other economic benefits. This would be the situation, for example, in the case of the new plutonium storage facility proposed by DOE.

Single-Purpose Use of Preexisting Facilities: Because in this case the use is still single purpose, all of the operating costs are still assignable to the plutonium disposition mission. Capital charges should only be assigned to the mission, however, to the extent that (i) they are associated with renovation or modifications of the facility that were required to enable it to perform the mission; or (ii) the facility had residual value in another role from which it is being displaced by the plutonium disposition mission. The capital costs of building the facility for its previous purpose should be ignored as "sunk" costs. In the case of the Pantex plant, for example, which now has little role other than the disassembly of nuclear weapons and the storage of the resulting plutonium, virtually all operating costs and capital modification costs—but not the original capital costs—should be charged to these missions.

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Multipurpose Use of Preexisting Facilities: This situation typically arises in connection with plutonium disposition approaches that generate electricity. But it also would apply, for example, to the incorporation of weapons plutonium into waste products being produced in facilities that would have to exist anyway for the purpose of disposing of high-level radioactive wastes. The costs that should be assigned to the plutonium disposition mission in such cases are only those attributable to the modifications (for purposes of plutonium processing) of the preexisting system, including any changes in operating cost and any replacement costs or avoided costs associated with decreased or increased outputs (such as changes in electricity production or the rate of waste vitrification) resulting from the addition of plutonium.

Multipurpose Use of New Facilities: If new facilities are constructed for the primary purpose of plutonium disposition but these also generate revenues (as from electricity or steam) or some other useful but unpriced product, the correct approach is to calculate the difference in cost between this approach and the cost of producing these same products in the way that they would otherwise be produced—known as the "avoided cost." In the case of electricity generation, calculations of avoided costs are routinely used but unavoidably contentious. In most areas of the United States, a reasonable figure for the avoided cost of electricity production is the cost of new combined-cycle natural gas generation capacity, roughly $0.05+/-0.01 per kilowatt-hour (expressed in 1992 dollars for the year 2015, the midpoint of a nominal 2000-2030 operating lifetime of a plutonium disposition reactor). The avoided-cost approach is obviously applicable, as well, to by-product services other than electricity, such as the production of tritium.

TABLE 3-5 Summary of Prescriptions for Costs Attributable to Plutonium Management and Disposition in Different Situations

	Preexisting Facilities	New Facilities
Single-purpose use	All operating costs plus incremental capital costs	All operating costs plus all capital costs
Multipurpose use	Incremental operating plus incremental capital costs	All operating plus capital costs less avoided costs

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ISSUES AND CRITERIA RELATING TO ENVIRONMENT, SAFETY, AND HEALTH

The greatest dangers to public welfare associated with the existence and disposition of weapons plutonium are unquestionably those connected with national and international security. The preeminence of these security dangers, however, should not obscure the need for careful attention to the environment, safety, and health (ES&H) risks implied by the different approaches to weapons dismantlement, fissile material storage, and long-term disposition of weapons plutonium.

As is well known, the U.S. nuclear weapons complex has left a heritage of ES&H problems, and those problems in the former Soviet Union's weapons complex are still worse. The United States is currently spending more than $6 billion a year on the cleanup effort, without making a significant dent in the problem so far. Damage from plutonium production, separation, and processing is a significant part of this ES&H legacy. It is essential that reductions in these vast nuclear arsenals not exacerbate these problems. The committee believes that the goal of reducing the security risks associated with excess nuclear weapons and fissile materials can and should be accomplished subject to reasonable ES&H constraints. It is very important that the governments involved express in the strongest terms their commitment to respect such constraints and demonstrate this commitment by promulgating an appropriate set of ES&H criteria for the plutonium disposition process. Additional institutional mechanisms and resources may be required.

The committee believes that in the United States these processes must:

1. comply with existing U.S. regulations (and subsequent modifications) governing allowable emissions of radioactivity to the environment, and allowable radiation doses to workers and the public from civilian nuclear energy activities;
2. comply with existing international agreements and standards (and subsequent modifications) covering radioactive materials in the environment; and
3. not add significantly to the ES&H burdens that would be expected to arise, in the absence of the weapons plutonium disposition problem, 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.

In Russia or other countries, the same criteria should apply, with the substitution of those countries' domestic regulatory framework for that of the United States.[10] (For a description of current U.S. and international regulations, see "Some Relevant Standards Limiting Doses and Emissions," p. 78.)

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[10] In some cases, this may mean that Russian activities will operate under less stringent criteria than in the United States. But insisting that finite ES&H funds in Russia be spent on fully complying with U.S. regulatory standards in the management of excess weapons and plutonium, when where is so

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In proposing this set of criteria, the committee understands that some may consider some of the relevant national and international regulations and guidelines unduly restrictive (meaning that they impose economic or other burdens disproportionate to their ES&H benefits), while others will argue that some are too lax. This study is not the place to examine these issues. The committee believes a formulation like the one proposed here should gain widespread acceptance as a practical basis for proceeding, and that it would be both unnecessary and unwise to allow the objectives addressed in this study to become hostage to reaching agreement on modifying any of the applicable national and international ES&H standards.

The committee believes that the criteria outlined above are both necessary and sufficient for ensuring adequate protection for ES&H. The first two criteria are necessary because to argue that looser standards are needed to get the job done would almost surely (given the history of similar claims by the nuclear weapons complexes in the United States and Russia) generate such strong opposition as to paralyze the processes of decision making and implementation. The resulting delay could seriously undermine the security goals driving the weapons plutonium disposition program. The third criterion is necessary because existing standards on emissions, doses, and disposition of radioactivity in the environment do not cover all of the ES&H characteristics of potential concern. To argue that the third criterion need *not* be met—that is, that management and disposition of excess weapons plutonium should be allowed to create a significant increase in the ES&H burdens of the nuclear weapons complexes or of civilian nuclear power—would also be likely to generate widespread objection and intolerable delay.

Interpretation of these criteria requires understanding the effects of ionizing radiation. Few if any classes of environmental hazards to human health have been studied more thoroughly than the radiological hazards from nuclear energy activities, but controversy remains. Most of the ES&H risks of plutonium management and disposition would involve low doses of radiation spread over long periods of time, and the effectiveness of such low doses in causing human cancers and other health effects is a subject of considerable uncertainty. Given the high background of cancer in the U.S. population (about 20 percent of all deaths), the long latency periods for cancer, the wide variations in behavior and other factors among the population, and the great variability of natural background radiation, it is difficult to establish a firm epidemiological basis for estimating the health effects of very low doses. The major national and international regulatory and advisory bodies dealing with radiation assume, for purposes of setting standards and estimating health effects, that the effect of radiation

much else to do in cleaning up the legacy of environmental contamination in the former Soviet Union, does not seem a wise request. For the states of the former Soviet Union to be able to achieve the objectives the committee outlines, however, while maintaining appropriate ES&H goals, may require special assistance.

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can be extrapolated linearly down to the level of natural background radiation, but this could be either an underestimate or an overestimate of the risk.[11] This linear assumption is particularly convenient because it means that a given "population dose"—the product of the size of the exposed population and the average dose to that population, measured in person-rem—would produce the same number of effects (primarily cancers) regardless of whether it was produced by a particular dose being given to a million people, or a hundredfold larger dose being given to 10,000 people. With this linear assumption, current

SOME RELEVANT STANDARDS LIMITING DOSES AND EMISSIONS

The relevant U.S. regulations are under the jurisdiction of the Nuclear Regulatory Commission (NRC) and the Environmental Protection Agency (EPA), and are described in the U.S. Code of Federal Regulations, Titles 10 and 40.[1]

The NRC standards limit the whole-body-equivalent dose to workers in the nuclear industry to 5 rem (0.05 Sv) per year.[2] NRC limits for members of the public include a 25-rem (0.25-Sv) whole-body once-in-a-lifetime emergency dose limit from a nuclear accident; a limit of 500 millirem (mrem) per year (5 millisieverts (mSv) per year) on the whole-body dose that could be received by an individual intruding inadvertently into a shallow burial site for low-level radioactive waste between 100 and 1,000 years after emplacement of the wastes; a limit of 100 mrem/yr (1 mSv/yr) on the whole-body dose from all routine nonmedical exposures combined; and a limit of 5 mrem/yr (50μSv/yr) each on the whole-body dose from routine airborne effluents and routine liquid effluents from any single nuclear facility. The EPA standards limit whole-body doses to the public to 100 mrem (1 mSv) per year from all nuclear facilities and 10 mrem (0.1 mSv) per year from any one nuclear facility.

Limits on emissions of radioactivity include an NRC limit on total emissions, except tritium and dissolved gases, of 5 Ci (0.19 TBq) per year from any nuclear reactor, and EPA limits on emissions from the entire nuclear fuel cycle, per electrical gigawatt-year of output, of 50,000 Ci (1,900 TBq) of krypton-85, 5 mCi (190 MBq) of iodine-129, and 0.5 mCi (19 Bq) of transuranics.[3] The emissions limits have been designed to ensure that the dose limits are met.

The international regulations of greatest potential relevance to the plutonium disposition issue are those governing disposal of radioactivematerial

[11] National Research Council, Committee on the Biological Effects of Ionizing Radiation, *Health Effects of Exposure to Low Levels ofIonizing Radiation* (BEIR V) (Washington, D.C.: National Academy Press, 1990).

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estimates suggest that for low doses over prolonged periods, one excess cancer death would be expected for every 2,500 person-rem of exposure, although this figure has wide bounds of uncertainty.

in the oceans. Under the 1972 Convention on the Prevention of Marine Pollution by Dumping Wastes and Other Matter in the Ocean (known for short as the London Ocean Dumping Convention), the International Atomic Energy Agency (IAEA) was charged with developing regulations to restrict dumping of radioactivity into the oceans to levels that pose "no unacceptable degree of hazard to humans and their environment." The resulting IAEA guidelines are based on the proposition that additions of radionuclides to the oceans should not exceed rates that, if continued for 1,000 years, would lead eventually to doses exceeding 100 mrem (1 mSv) per year to the most exposed individuals.[4] The models used by the IAEA to estimate these rates consider a variety of pathways by which humans could be exposed to radionuclides from seawater, including ingestion of fish, shellfish, seaweed, plankton, desalinated seawater, and sea salt; inhalation of evaporated seawater and airborne particulates originating from ocean sediments; and external irradiation from swimming and onshore sediments.

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[1] Office of the Federal Register, *Code of Federal Regulations*: Title 10 (Energy), Chapter I (Nuclear Regulatory Commission) (Washington, D.C.: U.S. Government Printing Office, January 1992), and Office of the Federal Register, *Code of Federal Regulations*: Title 40 (Protection of Environment), Chapter I (Environmental Protection Agency) (Washington, D.C.: U.S. Government Printing Office, January 1992).

[2] The dose in rem equals the specific energy absorption in rads (1 rad = 100 ergs per gram of tissue) multiplied by the Quality Factor (QF = I for x-rays, gamma rays, and beta particles; 10 for neutrons; and 20 for alpha particles). The corresponding SI unit is the sievert (1 Sv = 100 rem).

[3] One curie (Ci) is the radioactivity associated with 1 gram of radium-226 and amounts to 3.7 × 10-10 disintegrations per second. The corresponding SI unit is the becquerel (1 Bq = 1 disintegration per second = 2.7 × 10-11 Ci, 1 terabecquerel = TBq = 27 Ci).

[4] International Atomic Energy Agency, *Definition and Recommendationsfor the Convention on the Prevention of Marine Pollution by Dumpingof Wastes and Other Matter*, 1972, Safety Series No. 78, 1986 edition (Vienna: IAEA, 1986).

The argument for the sufficiency of the committee's three criteria has three parts:

1. The standards on emissions, doses, and disposition of radioactivity in the environment have been constructed to ensure that the radiological risks to the *most exposed* members of the public from the routine operation of nuclear facilities in compliance with these standards are much lower than the risks of the same types experienced by individuals in the same population

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from other causes. The doses to the *typical* workers or members of the public are much smaller than those to the most exposed.

2. Those radiological risks from plutonium disposition that would not necessarily be adequately limited by criteria 1 and 2 would be confined by criterion 3 to be a small addition to the risks of these kinds that exist or will exist from responsibly managed nuclear electricity generation and cleanup of the nuclear weapons complexes. Given that society is now bearing these risks in connection with the benefits of electricity supply and the need to manage the cleanup and consolidation of the nuclear weapons complexes, a small addition to them is not too high a price to pay for the security benefits of weapons plutonium disposition.
3. The nonradiological ES&H impacts from plutonium disposition—in such categories as the alteration of land and vegetation for facility construction, consumption of water, emission of chemical pollutants, and the usual array of industrial hazards to workers (falls, maiming by machinery, electrical shock, and so on)—would similarly be limited, by the implementation of criterion 3, to small additions to the current and projected risks of this kind resulting from civilian nuclear power and nuclear weapons complex cleanup. These nonradiological risks are in any case likely to be less significant for these missions than the radiological ones.

It would pose a genuine dilemma, of course, if the only dismantlement, storage, or disposition approaches capable of meeting reasonable security criteria turned out to be incapable of meeting reasonable ES&H criteria. The committee's review of the options argues, fortunately, that this is not likely to be the case. There is, however, a likely trade-off, as there often is, between meeting the sorts of ES&H criteria listed and conducting similar operations at minimum cost. Since the costs of the most promising approaches, even with these ES&H criteria included, are low compared to other costs involved in the pursuit of comparably important security goals—and since failure to meet such ES&H criteria could lead to public rejection and court challenges causing delays long enough to have major adverse security consequences—resolving the ES&H-economics trade-off in favor of the ES&H goals should be an obvious choice in this case.

ES&H and the Three Stages of Reductions

Dismantlement, fissile material storage, and long-term disposition of weapons plutonium can affect workers, members of the public now living, and future generations (as well as the nonhuman environment) in a variety of ways. Some effects result from the radiological properties of the materials used (such as cancer risks from inhalation of plutonium), and some result from nonradiological factors such as accidents similar to those that occur in other industries. They can also be divided into those that result from routine operations and

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those that result from accidents. In considering these issues, it is legitimate to focus on those ES&H impacts with the potential to be large enough either to affect choices concerning the most appropriate management approaches or to require mitigation efforts involving a significant fraction (perhaps 10 percent or more) of the total cost of the operation in question. As noted above, this is likely to mean radiological issues rather than nonradiological ones.

An assessment of the ES&H risks in these processes should focus, like the economic assessment, on the *net* effects of these activities in relation to what would have occurred had these excess weapons and materials not existed. As with the economic analysis, the two main possibilities are dealing with these weapons and materials in facilities that:

1. would have operated in any case (in which case what should be measured is the net additional ES&H impacts of involving the weapons plutonium in their operation); or
2. would not otherwise have operated (such as a reactor built expressly for that purpose).

In the second case, if the facility produces no other product, then the total ES&H impact of the operation must be charged against the plutonium disposition mission. If the facility does produce something that would otherwise be produced in other ways (such as electricity), then the ES&H impacts should in principle be compared to those of producing the same product in other ways. This may involve apples-and-oranges comparisons (such as comparing radiological effects of nuclear power to greenhouse effects of fossil fuels) that are so difficult as to be virtually impossible to undertake, so that it may be better simply to consider the total ES&H impact in this case as well.

Dismantlement

Dismantlement in general consists of activities that would not otherwise be taking place; therefore, their ES&H impacts must be charged completely to the reductions process. The main ES&H impacts of these processes are:

- risks of nuclear or conventional explosions during dismantlement (neither of these has ever occurred, at least in the United States);
- radiation exposure to workers in routine operations;
- radiation exposure to workers or the public in the event of accident (such as an accidental nuclear chain reaction);
- chemical exposures to workers and the public (for example, from the handling of hazardous materials in nuclear weapons or from burning conventional explosives); and
- risks from disposing of a variety of weapons components as waste.

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Compared to other activities in the nuclear weapons complex, dismantlement operations are relatively "clean," because no processing of nuclear materials is involved (see Chapter 4).

Intermediate Storage

The ES&H risks in storing fissile materials will depend significantly on the forms in which the material is stored, the processing (if any) required to convert available materials into those forms, and the design of the storage facilities. Another critical factor is the length of time over which storage is likely to extend, particularly if it is so long that there is some risk that ES&H protection measures might erode. The primary routine ES&H impact of plutonium storage would be radiation exposure to workers within the storage facility (such as those checking and moving the storage canisters, if these activities were not conducted robotically). The primary potential accidental ES&H impact of plutonium storage that must be guarded against is the potential for worker or public exposure to plutonium released in the event of an accident (for example, as a result of a plane crash, see Chapter 5).

Long-Term Disposition

In general, long-term disposition of plutonium is likely to be the stage with the most significant ES&H impacts, because it is likely to require substantial processing of plutonium and plutonium-bearing waste streams.

If long-term plutonium disposition is to be carried out in nuclear reactors, and those reactors would have operated anyway, the main changes from the operations that would otherwise occur would include:

- conversion of weapons plutonium metal to plutonium oxide (for LWRs and some other—but not all—reactor types);
- mixing the plutonium oxide with uranium oxide (for LWRs and some other reactor types) and fabricating the plutonium-bearing fuel;
- storage and transport steps associated with the preparation of the fuel, its delivery to the reactor, and its storage there prior to use;
- reduction in the amount of uranium mined, milled, converted, enriched, and fabricated, by virtue of the substitution of plutonium-bearing fuel for some of the uranium-only fuel that would otherwise have been used;
- any changes in the ES&H characteristics of reactor preparation, operation, and maintenance as a result of the use of weapons plutonium in its fuel; and
- any changes in the ES&H characteristics of waste management that result from the use of weapons plutonium in the fuel—including spent fuel storage and transport; further high-level-waste processing, if any; emplacement and residence in a geologic repository (including the potential long-term risks of

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criticality in the repository); and management of low-level and transuranic wastes.

Among these items, particular attention needs to be given to the possible impacts of weapons plutonium use on reactor safety and on the disposal of the resulting nuclear waste.[12] It should be noted that the additional troublesome ES&H issue in current nuclear power practice—the radiation doses to current and future generations from the tailings at uranium mines and mills—can only be diminished (albeit modestly) by the addition of weapons plutonium, since such addition would reduce the quantity of uranium that needed to be mined and milled. Among the ES&H issues that are *not* particularly problematic in current practice, the one most likely to need special attention with the addition of weapons plutonium is the occupational risk from fuel fabrication—where the far higher inhalation toxicity of plutonium per gram, compared to that of uranium, calls for special precautions that add significantly to the cost of fabrication.

If the plutonium is mixed with high-level nuclear wastes in a method of processing and managing these that would have been used anyway (such as vitrification), the alterations to the baseline waste operations that would need to be considered include:

- conversion of the weapons plutonium metal to whatever form is required as input to the waste-processing operations, and of transporting the plutonium to the waste-processing facility and storing it there;
- addition of the plutonium to the ES&H characteristics of the waste-processing operations, including particularly any potential criticality problems in waste processing and storage, and of measures taken to offset this potential; and
- effects of plutonium addition on the ES&H characteristics of waste storage, transport, and emplacement and residence in a geologic repository (including the potential long-term risks of criticality in the repository).

Although all of these alterations to the baseline effects of waste operations will need attention, the second and third can be expected to be the most difficult.

As noted above, in cases where long-term disposition involves primarily activities that would not otherwise have been undertaken, one must demonstrate that the total ES&H impacts are not unreasonable in exchange for the benefits of the operation—that is, reducing the plutonium's security risk.

In the case of use in reactors, public concern has rightly focused on the risk of reactor accidents. Available probabilistic risk assessments of the risks of reactor accidents involve substantial uncertainties. Nevertheless, the available data, with all the caveats that must be attached to them, indicate that the health

[12] Both of these issues are addressed in more detail in *Managementand Disposition of Excess Weapons Plutonium: Report of the Panelon Reactor-Related Options* (op. cit.).

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and safety impacts of current nuclear electricity generation in the United States are not unreasonable either in absolute terms or in comparison to the impacts of the main current source of U.S. electricity supply (coal). Hence, the committee believes the ES&H standards it has outlined can be met for the case of reactors that would not otherwise operate, as long as the addition of plutonium does not significantly increase the ES&H impacts of these reactors. Therefore the analysis must focus on the additional risks resulting from plutonium use, in a way similar to those for reactors that would be operating in any case.

For the disposal options, the most important single ES&H issue in most cases will be preventing plutonium release into the environment (including over the very long term) in ways that would violate regulatory criteria. Accident scenarios, of course, must be considered in these cases as well.

OTHER CRITERIA

In addition to the security, economic, and ES&H criteria just described, approaches to management and disposition of excess weapons plutonium must be acceptable to both the public and the relevant institutions, and should, to the extent possible, avoid conflict with other policies and objectives.

Public Acceptability. Without public acceptance, successful implementation of any management and disposition approach is unlikely. Gaining public acceptance will require attention to ES&H protection, as described above, and encouraging a decision-making process with genuine public participation, both local and national.

Institutional Acceptability. Similarly, acceptance by the various institutions that must give their approval will be a critical factor in the success of any management and disposition approach. Licensing in particular is likely to be a pacing factor in many cases, and clearly predictable difficulties in this regard could affect the choice of options. As with the public, early participation by the relevant institutions is essential.

Other Policies and Objectives. Management and disposition of excess weapons plutonium should, as with other activities, be guided by the agreements, laws, regulations, and policies of the state carrying it out. Where a particular approach would appear to contravene existing international agreements, for example, the committee considered this a major obstacle.

Similarly, management and disposition of excess plutonium should ideally proceed in a manner supportive of the other policies of the state carrying it out. This includes, in particular, policies related to nonproliferation and nuclear fuel cycles. The committee does not believe, however, that promoting the future of civilian nuclear power—or the reverse—should be considered a significant criterion for choice among options for disposition of weapons plutonium. That future depends on broader economic, political, and technical factors outside the

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scope of this study. The committee also does not believe that whether plutonium disposition options would also have the potential to produce tritium should be a major criterion for deciding among them. (These subjects are addressed in more detail in Chapter 6.)

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Declarations and Dismantlement

The nuclear weapons and fissile materials that will become excess as a result of arms reductions are only a part of the world stocks of these items (see Chapter 1). Thus the measures taken to address the urgent problem of managing *excess* nuclear weapons and fissile materials—from dismantlement of weapons through storage and long-term disposition of the resulting fissile materials—must be seen not only as ends in themselves, but also as steps toward an overall regime designed to achieve higher standards of security and transparency for the *total* stocks of weapons and fissile materials in the United States and the former Soviet Union—and, ultimately, worldwide. The committee envisions a reciprocal regime, built in stages, that would include:

1. reciprocal declarations of total stocks of nuclear weapons and fissile materials;
2. cooperative measures to confirm and clarify those declarations;
3. agreed, monitored subtractions from the stocks available for military use, including:
    - monitored warhead dismantlement,
    - commitments never again to use agreed quantities of fissile materials for weapons purposes,
    - safeguarded storage and long-term disposition of excess fissile material stocks, and

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4. agreement on and monitoring of additions to those stocks, including whatever warhead assembly continues, and a verified cutoff of production of fissile materials for weapons.

Such a regime, if agreed between the United States and Russia, would directly serve the three security objectives outlined at the beginning of this report—limiting the risk of theft, limiting the risk of breakout, and strengthening arms reduction and nonproliferation. It would also provide a sound base for building a similar global regime. Although complex and far-reaching, such a regime can be approached incrementally, contributing to confidence at each step while posing little risk. Measures specific to excess weapons and materials, such as monitoring of warhead dismantlement (discussed in this chapter) and secure, safeguarded storage of excess fissile materials (discussed in the next chapter), will be essential building blocks of this larger regime.

Virtually none of this broad regime is currently in place. But the end of the Cold War offers an opportunity to begin building it that is both unprecedented and unlikely to be repeated. The Clinton administration, in its nonproliferation initiative of September 27, 1993, has taken the first steps in this direction, announcing that it would propose a global convention to ban production of fissile materials for weapons and that it would voluntarily submit excess U.S. fissile materials to International Atomic Energy Agency (IAEA) safeguards.[1] In addition, on December 7, 1993, Energy Secretary Hazel O'Leary declassified the amount of weapons-grade plutonium that the United States has produced and the amounts held at several Department of Energy (DOE) sites.[2] More remains to be done, however.

Weapons and fissile materials in the former Soviet Union are currently of greater concern than those in the United States. Achieving substantial improvements in the management of these weapons and materials in the former Soviet Union, however, will in many cases require reciprocity from the United States.

THE CASE FOR A BROAD REGIME

Some more limited objectives can be achieved by efforts focused only on excess weapons and materials—such as the highly enriched uranium (HEU)

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[1] White House Fact Sheet, "Nonproliferation and Export Control Policy," September 27, 1993.

[2] Secretary O'Leary announced that the United States had produced 89 metric tons of weapons-grade plutonium. In addition, the Hanford site produced 13 tons of reactor-grade plutonium. DOE also declassified the total current plutonium inventory at Savannah River, Rocky Flats, Hanford, Los Alamos National Laboratory, Lawrence Livermore National Laboratory, Argonne National Laboratory-West, and Idaho National Engineering Laboratory. But the "total quantity of plutonium at Pantex remains classified due to a proliferation concern that the amount of plutonium in a nuclear weapon could be determined by correlating the number of dismantlements being released to the public, to future increases in the plutonium inventory." The DOE press release also stated that "today's release should be considered only a beginning of a process." *DOE Press Release*, December 7, 1993.

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purchase under negotiation and the planned fissile materials storage site to be built in Russia with U.S. assistance. But measures focused only on these excess stocks would leave the size and status of the other stocks unknown. Creating a broader regime covering the total stockpiles of nuclear weapons and fissile materials would make clear that this total stock was of legitimate interest to the world community and would have the following specific benefits:

- *Strengthening Current Arms Reduction Agreements:* Measures to verifiably eliminate the warheads to be retired under recent arms agreements, monitor the resulting fissile material, and build confidence that there were not other large, unmonitored stocks of excess weapons and materials available would substantially strengthen the arms reduction regime, complementing the limits on launchers in the Strategic Arms Reduction treaties (START I and START II). Such measures would work synergistically with the measures already agreed, to make rearmament more difficult, costly, time-consuming, and observable—and therefore less likely.
- *Providing the Basis for Deeper Reductions:* Similarly, a regime for agreed, monitored, balanced reductions in the stockpiles of nuclear weapons and fissile materials would lay a foundation for deeper, post-START II nuclear arms reductions. Without a regime designed to build confidence over time in the knowledge of the stockpiles of weapons and fissile materials, concerns about the military advantage that might be gained by retaining large hidden stocks could make the United States, Russia, and other nuclear powers reluctant to agree to reduce to substantially lower levels.
- *Improving Resistance to Theft:* Such a wide-ranging regime would provide the basis for significantly improving security and safeguards for nuclear materials, particularly in the former Soviet Union, where the current dramatic political and economic transformation necessitates strengthening these vital functions. In order to make comprehensive improvements, it is essential to have an understanding of how large the stocks of fissile materials are, where they are located, and the like. The requirement to provide declarations would focus each party to the regime on the task of accounting in detail for all the material in its possession and reviewing its own management procedures. Moreover, the declarations and the visits involved in confirming them would provide a more educated basis for U.S. offers of assistance to Russia in improving safeguards and security, allowing discussions on this subject to be more meaningful and comprehensive, and less impeded by secrecy (see Chapter 5).
- *Strengthening the Nonproliferation Regime:* Including monitored subtractions from the total stocks of nuclear weapons and fissile materials in the arms reduction regime would help convince the rest of the world that the nuclear states were seriously pursuing their obligations under Article VI of the Non-Proliferation Treaty (NPT). Indeed, a number of non-nuclear-weapon states have specifically called on the United States and Russia to agree to such measures. In particular, agreement on the first steps toward such a regime

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during preparations for the critical 1995 NPT review would help create a favorable atmosphere for an indefinite or long-term extension of the treaty. Similarly, a new openness and willingness to accept international monitoring on the part of the largest nuclear powers would improve the prospects for gaining acceptance of strengthened safeguards elsewhere. Applying strict standards of security and accounting to excess fissile materials resulting from arms reductions could provide the base for setting similar standards for civilian fissile materials worldwide (see below).

- *Providing Information:* Current public knowledge of the stockpiles of nuclear weapons and fissile materials is limited, although as noted above, the United States has recently begun declassifying some of this information. As yet, Russia has not reciprocated. Total inventories of weapons and the size of reserves and "excess" stocks have not been authoritatively disclosed by either country. The uncertainties in U.S. intelligence estimates of Russian stocks amount to thousands of weapons and tens of tons of fissile material.[3] Each side's intelligence services have in the past spent billions of dollars attempting to acquire the information that would be exchanged under this regime. Such information provides a basis for defense and arms control planning; for coordinating efforts such as the HEU purchase and the planned plutonium storage site in Russia; and as mentioned, for more educated offers of assistance in managing these weapons and materials.
- *Building Confidence:* Establishing such a regime of transparency and reductions in nuclear weapons and fissile materials would reflect and deepen the significant Russian-American cooperation in denuclearization. Experience to date with agreements such as the Strategic Arms Limitation Treaties (SALT I and II), the Intermediate-Range Nuclear Forces Treaty (INF), the Conventional Forces in Europe Treaty (CFE), and START I and II suggests that working together to reach agreement on reductions, declarations, and monitoring, and then to implement those agreements, has a far-reaching confidence-building effect. Indeed, the exchange of information alone has generally proved helpful in resolving uncertainties and concerns, even in cases where the data initially provided were not immediately accepted as accurate.[4] Such a regime could

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[3] Lawrence Gershwin, National Intelligence Officer for Strategic Programs, told Congress in 1992, that the Central Intelligence Agency estimated that Russia then had 30,000 nuclear weapons. "The uncertainty is plus or minus 5,000, which gives you a sense of how uncertain it is. That uncertainty has not improved … because we still don't get direct information on how many weapons are at sites and how many are in inventory." See House Defense Appropriations Subcommittee, *Department of Defense Appropriations for 1993*, Pt. 5, p. 499, May 6, 1992. Recent statements by Victor Mikhailov, Russia's Minister of Atomic Energy, suggesting that Russia had significantly larger stockpiles of weapons and HEU than previously believed, have highlighted those uncertainties (see Chapter 2).

[4] In the case of the CFE treaty, for example, the requirement to exchange information provided each party with a wealth of hitherto unavailable information. Although initial Soviet data on treaty-limited items in the limitation zone were not accepted, it was the requirement for full reporting itself that provided the basis for questioning the Soviet figures and ultimately resolving the issue; in the end, few would argue that the declarations required by CFE were not a useful, indeed essential, part of the CFE regime. Given the large quantities of nuclear weapons and materials that would have to be accounted for in a regime such as

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address some concerns that have undermined confidence: for example, in both the United States and the former Soviet Union, opponents of the ongoing reductions have pointed to the lack of any requirement to verifiably dismantle the weapons to be retired as a key justification for continuing suspicion.

- *Improving Democratic Management:* In democracies the information needed to make decisions on security and related issues should be available to the public. Secrecy in this area has affected not only security debates but environment, safety, and health (ES&H) discussions as well, since the United States and Russia have been reluctant to release ES&H information that might provide details of weapons or fissile material production. The committee shares the view of President Reagan's Blue Ribbon Task Group on Nuclear Weapons Program Management:

> One of the national security responsibilities of DOE leadership is to make available sufficient information to allow informed public debate on nuclear weapon issues. The Task Group urges that DOE review its classification procedures to ensure that criteria are based upon current requirements rather than historical precedent.[5]

The Secretary of Energy has statutory authority under the Atomic Energy Act to declassify restricted data, and Secretary O'Leary has begun what she has said will be a continuing process with the declassification of some plutonium stockpile data on December 7, 1993. In addition, the 1993 Defense Authorization Act specifically granted authority to declassify stockpile information if the United States and Russia reach agreement on reciprocal release of such data.[6]

In Russia, some organizations with major responsibilities in these areas (such as the Foreign Ministry and GOSATOMNADZOR, the Russian equivalent of the Nuclear Regulatory Commission) appear not to have access to information relating to nuclear stockpiles that is necessary to carry out their duties.[7] The need to provide this information to the United States would

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that envisioned in this chapter, and the long time over which they were produced, ambiguities can be expected in this case as well, requiring similar efforts to resolve them.

[5] "Report of the President's Blue Ribbon Task Group on Nuclear Weapons Program Management," July 1985, p. 13, cited in Energy Research Foundation and Natural Resources Defense Council, *Rethinking Plutonium: A Reviewof Plutonium Operations in the U.S. Nuclear Weapons Complex* (Washington, D.C.: April 1992), pp. 52-53.

[6] The primary relevant language from the Atomic Energy Act is Section 142: "(a) The Department [of Energy] shall from time to time determine the data, within the definition of Restricted Data, which can be published without undue risk to the common defense and security and shall thereupon cause such data to be declassified and removed from the category of Restricted Data." In the case of Restricted Data determined to "relate primarily to the militarization of atomic weapons," this determination must be done jointly with the Department of Defense. The recent modification to this language appears in the conference report on the Department of Defense Authorization Act, Report 102-966, October 1, 1992, p. 338.

[7] For example, while President Yeltsin has given GOSATOMNADZOR responsibility for regulating safeguards and security over both military and civilian nuclear materials in Russia, GOSATOMNADZOR officials report that they have been denied the access to information and facilities necessary to carry out this responsibility. See Mark Hibbs, "Watchdogs Say MINATOM Withholding Material Theft and Diversion Data," *Nuclear Fuel*, August 16, 1993; and "Uranium, Plutonium, Pandemonium," *The Economist*, June 5, 1993.

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inevitably make it available to wider circles in Russia, beneficially broadening participation in decision making—itself potentially a major step toward improving the management and security of fissile materials in Russia.

- *Providing Incentives:* Some have proposed that the United States provide direct incentives, monetary or otherwise, to the states of the former Soviet Union for steps such as accelerating dismantlement or committing fissile material to peaceful purposes under monitoring. This is part of the idea behind the HEU deal: for example, dismantlement would free HEU that in turn would earn hard currency, providing a direct incentive for the dismantling.[8] If such incentives are to be offered, there must be a means to check that the specified goals are being met, which a transparency regime would provide.
- *Strengthening Management Organizations:* In Russia, the Ministry of Atomic Energy (MINATOM) and the military are struggling to meet the challenge of managing the large-scale reductions now in progress in the midst of a drastic weakening of central authority, the disappearance of their traditional Cold War missions, and drastic declines in their former budgets and status. Substantial erosion of these organizations could greatly increase the risks of theft of nuclear weapons and fissile materials. A regime based on cooperation in nuclear reductions, combined with appropriate incentives for accomplishing particular tasks (such as warhead dismantlement and secure management of warheads and fissile materials) could provide these organizations with a new and compelling mission to replace their old tasks —and with the resources needed to carry it out.

  Similarly, if structured to utilize and expand on the capabilities of international organizations—particularly the IAEA—the regime the committee proposes could significantly bolster their ability to carry out their global nonproliferation roles.
- *Addressing Some Ukrainian Concerns:* Ukrainian officials have repeatedly expressed concern that if they fulfill their denuclearization pledges and ship the nuclear weapons now on their territory back to Russia for dismantlement, Russia might add the weapons or the materials in them to its own military stocks. Although the key Ukrainian nuclear concern is the more general security threat it perceives, Russian willingness to permit Ukrainian monitoring of the dismantlement of weapons removed from Ukrainian territory has been an important factor in discussions of this issue. A broader regime would go further in addressing these Ukrainian concerns.

Data," *Nuclear Fuel*, August 16, 1993; and "Uranium, Plutonium, Pandemonium," *The Economist*, June 5, 1993.

[8] The United States has now agreed, however, that it will not insist on transparency measures to guarantee that the HEU it purchases came from dismantled weapons rather than from excess stocks. Since Russia could therefore continue the deal for a number of years without dismantling any additional weapons, this fact may significantly limit the effect of the agreement as a dismantlement incentive.

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In 1992, a similar list of objectives led the U.S. Senate to attach the so-called Biden Condition to its resolution of advice and consent to ratification of the START I treaty, citing the risk of "loss of control of nuclear weapons or fissile materials in the former Soviet Union" and requiring the president to seek an arrangement to monitor the total stockpiles of nuclear weapons and fissile materials in the former Soviet Union and the United States, using "reciprocal inspections, data exchanges, and other cooperative measures." This condition is legally binding on the U.S. government, though when it must be carried out was deliberately left ambiguous.[9]

Indeed, some elements of the regime the committee envisions have been official U.S. proposals in the past. In 1953, President Eisenhower, in his Atoms for Peace speech, called for transfers of specific quantities of fissile materials from military stockpiles to civilian purposes under international safeguards. The idea of cutting off production of such materials and shifting some of the existing stocks to civilian purposes—known as "cutoff and transfer"—was a major element of U.S. arms control proposals for many years thereafter. By 1965, this proposal had evolved into a formal U.S. proposal for monitored destruction of thousands of nuclear weapons and transfer of the resulting fissile materials to civilian stockpiles.

Building such a regime will not be easy, however, despite the compelling motivations to do so. Far-reaching changes in the way the nuclear weapons complexes in both the United States and the former Soviet Union do business will be required, including the exchange of substantial quantities of information that is currently classified.[10] The committee is convinced, however, that declassification of this information would advance U.S. security and nonproliferation objectives.

In principle, the most sensitive information related to stocks of weapons and materials would be the numbers and locations of currently deployed strategic forces, because of the possibility of an attack on those forces. Yet that information has been exchanged in great detail as part of the START I agreement.

[9] Specifically, the condition requires that the President "seek" such an arrangement "in connection with any further agreement reducing strategic offensive arms," including START II. Arguing that a requirement to reach such an agreement in parallel with START II could seriously delay that treaty, the Senate Armed Services Committee, under the chairmanship of Senator Sam Nunn, opposed the Biden Condition in its report on the START treaty. But when the subsequent Foreign Relations Committee report specified that the "in connection with" language was not intended to prevent action on START II in the absence of such an arrangement, Senator Nunn withdrew his opposition, and the treaty, with the attached condition, was approved overwhelmingly by the Senate. In May 1993 testimony to the Senate Foreign Relations Committee, Secretary of State Warren Christopher acknowledged that no action had yet been taken to implement the Biden Condition, but indicated that the administration intends to fill this gap.

[10] In particular, a range of information related to the size and location of all parts of the stockpiles of nuclear weapons and fissile materials, and information related to the weapons components—specifically the amount of fissile material they contain—could be declassified as part of the regime proposed here. If, in some cases, the amount or isotopic composition of fissile material in particular components was considered sensitive, somewhat more complex monitoring arrangements could be devised that would provide confidence in overall figures without revealing those related to a particular specific device.

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It is difficult to argue that the numbers and locations of weapons that are not deployed, or of materials that are not fabricated into weapons, are more sensitive than those of weapons that are part of the active military force. Thus, it is difficult to justify the current practice of releasing information on all deployed strategic delivery systems, while keeping information about the corresponding weapons and about most aspects of the stocks of fissile materials secret. As already noted, DOE has begun to address this issue with the release of some information about plutonium stocks.

Objections that might be raised against a declaratory regime are similar to those introduced when inventory declarations became part of the INF treaty, START I, and START II; yet the parts of those regimes involving declarations, verification, and reductions that have been carried out to date have proven beneficial. A traditional objection is that if the other party underdeclares its holdings and keeps a secret stock, it could gain a significant advantage if drastic reductions were carried out. Clearly, however, that is more an argument against the drastic reductions than against the exchange of information. Moreover, the argument simply reinforces the case that deep post-START II reductions may be impossible to achieve without greater confidence in each party's knowledge of the other's stocks of nuclear weapons and fissile materials. Another argument occasionally heard is that ignorance of the total stockpile itself keeps the opponent guessing and therefore has some deterrent effect. Yet in an age of cooperation, transparency is more stabilizing than ignorance.

Such a regime would involve costs for the associated monitoring and cooperative measures. Monitoring of warhead dismantlement, for example, would probably require a permanent foreign presence at the dismantlement sites. These costs would probably be in the range of tens of millions of dollars per year for each side (not counting the costs of dismantlement itself).[11]

Russian Attitudes. Russian officials have expressed differing views concerning the different parts of such a regime. On February 12, 1992, Russian Foreign Minister Andrei Kozyrev, in a comprehensive statement to the United Nations Conference on Disarmament in Geneva, called for "a reciprocal exchange of data between all nuclear powers on the number and types of existing nuclear weapons, the amount of fissionable materials, and on nuclear weapons production, storage, and elimination facilities." This proposal, however, was never pursued by either side, and officials at MINATOM and other agencies

[11] To verify warhead dismantlement at existing facilities, a single perimeter-portal monitoring system would be needed in the United States (at Pantex), and several in Russia. The existing perimeter-portal monitoring system at Votkinsk cost $45-$50 million to install, with an annual operating cost of $10-$20 million. (See U.S. Congress, Congressional Budget Office, *U.S. Costs of Verification and ComplianceUnder Pending Arms Treaties* (Washington, D.C.: U.S. Government Printing Office, September 1990).) The IAEA safeguards more than 1,000 installations worldwide (see Table 2-1), with an annual safeguards budget of $60-$70 million, though a few of these facilities (particularly enrichment, reprocessing, and plutonium fuel fabrication plants) account for a disproportionate share of the safeguards costs. The proposals outlined in this chapter might require roughly doubling the annual IAEA safeguards budget.

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have expressed considerable resistance to such broad-ranging transparency. More recently, on August 17, 1993, Russia's representative to the Conference on Disarmament reiterated Russia's willingness to agree to a verified cutoff of production of fissile materials for weapons, to put excess fissile materials under IAEA safeguards, and to exchange information relating to such materials, on the basis of reciprocity. Agencies other than the Foreign Ministry, however, may continue to have different views. The most consistent theme the committee has heard from Russian officials is that anything more than the most limited transparency measures would require reciprocity from the United States, which U.S. negotiators have so far not been prepared to offer.[12] The committee believes that persistent diplomacy by the United States, coupled with offers of reciprocal openness and continued financial assistance, would stand a good chance of overcoming the obstacles to taking the steps outlined in this chapter.

Such a regime must be built in stages. Determining which steps should be pursued in which order is primarily a matter of negotiating tactics, a subject beyond the scope of this report. But urgency is in order. In the current environment of reasonably cooperative relations between Russia and the United States, a deliberate effort to understate the stocks and maintain substantial secret stockpiles appears unlikely. The more information exchanged while this remains the case, the more difficult it will be to create a secret stockpile in the future. Translating general good will into substantial understanding removes the seeds of suspicion and protects against the worsening of political relations.

IMPLEMENTING A BROAD REGIME

Fissile materials and nuclear weapons have a complex life cycle including mining, milling, processing, and enrichment of uranium; production of plutonium in special reactors; separation of the plutonium from the highly radioactive "targets" from those reactors; fabrication of fissile material weapons components; assembly of nuclear weapons from these and other components; deployment of nuclear weapons; retirement and disassembly of nuclear weapons; and storage and eventual disposition of fissile materials.[13]

The regime envisioned in this report would apply a variety of measures to different parts of this life cycle. The measures involved should be seen as mutually reinforcing, working together to build confidence that the information exchanged was accurate and that the goals of the effort were being met.

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[12] For a list of the Russian institutions the committee visited during a visit to Moscow in May 1993, see Appendix A.

[13] For a useful short description of this life cycle, see National Research Council, *The Nuclear Weapons Complex: Management for Health,Safety, and the Environment* (Washington, D.C.: National Academy Press, 1989), Appendix B. In both the United States and Russia, the actual deployment and operation of nuclear weapons is the only part of this process controlled by the military. The rest of the process is controlled by the department in charge of nuclear energy, the Department of Energy in the United States and Ministry of Atomic Energy in Russia.

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Although it is true that technical measures are not available to verify the total stockpiles of nuclear weapons and fissile materials with great accuracy, such a network of measures could build confidence over time—much as a bank audit, which never counts all of the money in a bank's possession, builds confidence that the bank's records are basically accurate.

Stockpile Declarations and Monitoring

The fundamental basis for an overall regime would be a series of declarations by each party to the regime, specifying its holdings of nuclear weapons and fissile materials. Consideration would have to be given to how and in what sequence the various categories of weapons and fissile materials should be addressed. In addition, declarations would include locations of stockpiles, as well as descriptions of plutonium production and uranium enrichment plants, facilities for fabricating fissile material weapons components, and nuclear weapons assembly and disassembly facilities.

In general, confirming that particular declared facilities held the items declared would be relatively straightforward. If it were considered too sensitive to provide full information on the locations of all inventories of weapons and materials at all sites, various sampling techniques might be used.[14] The key advantage of declaring all major sites is that any weapons or materials detected outside those sites would then be clear evidence of a secret stockpile.

The more difficult problem will be assessing whether there are significant undeclared stocks at undeclared sites. This problem could be partly addressed through three primary approaches:

1. National intelligence already provides rough estimates of other nations' holdings of nuclear weapons and fissile materials, which could be checked for consistency with declarations—although, as noted, uncertainties in U.S. estimates of Russian stocks are currently large. Such national means of intelligence were the sole means of verifying arms agreements such as the SALT treaties, and remain an essential foundation for verification of more recent agreements incorporating on-site inspection. But because nuclear weapons and fissile

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[14] For example, each side might tag all the weapons in its possession (a process known as "self-tagging") and provide the other with a list of the tag numbers; various sampling schemes under which one side could demand to see the weapons corresponding to particular tag numbers could then be envisioned, without revealing the locations of the entire stock of weapons. A conceptually similar approach might be implemented without the existence of physical tags: each side might provide the other with a table containing the locations and serial numbers of every weapon in its stockpile—but in encrypted form, so that the table could not be read. (Both sides already rely for their national security on the success of their encryption technologies for transmitting sensitive information.) The table could then be "de-encrypted" one line at a time for the purposes of inspection. For example, inspectors visiting a declared site might demand to see the line in the table representing a particular warhead at that site. A warhead that did not have such a line on the table would then be evidence of violation. For more on this concept, and other means of monitoring warhead and fissile material stockpiles, see S. Drell et al., "Verification of Dismantlement of Nuclear Warheads and Controls on Nuclear Materials," JASON, MITRE Corporation, JSR-92-331, January 1993.

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materials are much smaller than long-range missiles or bombers, and do not necessarily have comparable operational signatures, national technical means of intelligence will be less effective in monitoring them, and there will inevitably be less confidence in the accuracy of declared inventories. A number of techniques have been applied over the years: releases of krypton-85 from reprocessing plants, for example, have provided considerable information on production of separated plutonium. Power consumption at enrichment facilities, heat output from production reactors, and similar data have helped round out the picture of fissile material production. Intelligence has also provided some information on which to base estimates of nuclear weapons production and deployment.

2. In addition to providing baseline estimates against which declarations could be compared, national intelligence might detect stockpile activity outside declared sites, or other information that clearly contradicted the exchanged declarations—a possibility that would help deter any party that contemplated maintaining either a secret stockpile or secret production facilities.
3. Exchanges of operating records of major production sites, followed by visits to those sites, could help confirm the information exchanged and reduce the uncertainties in unilateral intelligence. Certain characteristics of reactor buildings, waste from reprocessing, and tailings from enrichment plants can help determine how much material was produced and when, and these findings can be compared to the operating records for consistency. The latter techniques, sometimes known as "nuclear archaeology," are still being developed and cover a broad spectrum.[15]

Physical and radiological examination of the interior of plutonium production reactors, for example, can provide information about both their design and the power levels at which the reactor has operated over its history. There are important uncertainties involved in this approach, however, including complications introduced by replacement of reactor parts and changes in design over time. Examination of the reprocessing wastes where the plutonium was separated can also provide some information, though for programs as old, large, and diverse as those of the United States and the former Soviet Union, this information is likely to be limited.

Enrichment facility operating records can be checked for consistency with the tailings of depleted uranium that they produce as waste: examination of the various isotopes in these tailings can indicate when the uranium was enriched, and whether it was enriched only to a few percent or to weapons-grade.

[15] For a general description of these concepts, see, for example, Steve Fetter, "Nuclear Archaeology: Verifying Declarations of Fissile-Material Production," *Science & Global Security*, no. 3, 1992, pp. 237-259. These techniques are also extremely important in a nonproliferation context—as the IAEA's current efforts to verify past production in North Korea and South Africa make clear. It might therefore be helpful for the two sides, in parallel with the confirmation effort, to undertake a joint research effort to refine these approaches further.

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Unfortunately, weapons assembly and disassembly facilities are not susceptible to such checks of the consistency of the physical status of the facility with operating records. Numbers of nuclear weapons can to a limited degree be checked for consistency with numbers of weapon systems with which they are associated, though the existence of spares, reserves, testing units, and reloads would complicate that approach considerably. As noted above, numbers at declared sites can be checked by routine inspection, and some provision for limited challenge inspections (comparable to those that have been worked out in other recent agreements) would also be useful.

Ultimately, while no combination of intelligence and examination of books and facilities could ever prove that declarations were complete, it could go a long way in building confidence—and any effort to hide a large stockpile that was not very carefully prepared, so that all the false information provided matched the physical state of existing facilities in a consistent way, would stand a substantial probability of detection.

There is also the possibility of secret facilities producing fissile materials or weapons. In general, however, over the period of time necessary to build a strategically significant illegal stock, unilateral intelligence should be capable of detecting covert production on a scale large enough to be of military significance. Such secret facilities are of more concern in a nonproliferation context, in which the problem is to detect production of one or a few nuclear weapons.

As noted earlier, if declarations were made in the current climate of cooperation, the probability of Russia's deliberately hiding a significant part of its stockpile of weapons or materials seems low—and once a good faith declaration was made, it would be more difficult for future governments to generate such a secret stockpile. Moreover, in the new environment in the former Soviet Union, with nascent democracies, strong political disagreements, and a newly open press, it is more difficult to keep such secrets than it once was. The possibility of "whistleblowers" would provide an additional deterrent to large-scale violation. The recent case of a Russian chemist revealing a continuing Russian chemical weapons development effort—and then being arrested—indicates both the potential and the limits of this source of arms control verification information.[16]

These problems of "initialization"—that is, determining whether the declared initial inventory of items to be limited by arms control is correct—have also been addressed in the INF, START, and CFE treaties, as well as the Chemical Weapons Convention (CWC). In the end, despite some problems, the agreed data bases and accompanying confirmation measures in all of these regimes have been considered beneficial. The same should be true of a declaratory regime for nuclear weapons and fissile materials.

[16] See, for example, Frank von Hippel, "Russian Whistleblower Faces Jail," *The Bulletin of the Atomic Scientists*, March 1993; and Will Englund, "Ex-Soviet Scientist Says Gorbachev's Regime Created New Nerve Gas in '91," *Baltimore Sun*, September 16, 1992.

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The committee concludes that U.S. knowledge of the stockpiles of weapons and fissile materials in Russia could be substantially improved through declarations and cooperative measures to help confirm them, for which a variety of potentially promising approaches are available. Such measures, however, could not eliminate potentially significant uncertainties regarding the possibility of covert stocks.

Monitoring Dismantlement

Dismantlement—the fundamental means by which nuclear weapons are subtracted from the total stock—is one of the three stages in managing excess plutonium resulting from arms reductions; it is treated in a separate section below.

Monitored Storage of Excess Fissile Material

Similarly, the commitment of excess fissile materials to peaceful use or disposal and the monitoring of storage and disposition to confirm that commitment—the means by which fissile materials are subtracted from the stocks available for military use—are fundamental to the subject of this report and are discussed in Chapter 5.

Monitoring Assembly

Keeping track of dismantlement is intended to provide an understanding of subtractions from the declared stockpile of nuclear weapons. In order to know the *net* subtraction from the stockpile, it would be necessary to monitor assembly as well, though assembly might be subject to somewhat different procedures because of its possibly greater sensitivity. This issue is addressed below, in the discussion of dismantlement.

A Fissile Material Production Cutoff

Similarly, if agreed transfers of fissile materials to civilian stocks are to be a useful arms control measure, it is important to ensure that new military fissile materials are not produced to replace them. Combined with the monitored transfer of large quantities of existing materials to peaceful purposes, cutting off production of fissile material for weapons would provide a demonstrable sign of progress in arms reduction, capping and reducing the total potential size of the nuclear arsenals that could be produced. The United States has already stopped producing all fissile materials for weapons and has recently proposed a global convention ending such production. Russia has stopped producing HEU but continues to produce weapons-grade plutonium, and has expressed willingness to agree to a formal production cutoff.

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Ironically, at present Russia is continuing to produce weapons plutonium while requesting assistance to address the shortage of available space to store it (see Chapter 5). The Russian government has indicated that the remaining three plutonium production reactors provide necessary heat and power to the areas surrounding them, and that their spent fuel must be reprocessed for logistical and safety reasons, but it has announced plans to end production of weapons plutonium by the year 2000. The U.S. government has begun discussions with the Russian government concerning possible assistance in converting these reactors or providing alternate sources of power so that weapons-grade plutonium production can be cut off in the near term. Particularly as a cutoff of production plays a central part in the Clinton administration's September 1993 nonproliferation initiative, the committee believes it is essential, for both substantive and symbolic reasons, that this continuing Russian production of weapons plutonium be ended expeditiously. The politics of other issues, such as the future of nuclear power and nuclear safety in Russia, should not be allowed to interfere with assistance in shutting down this production as soon as possible. Technical means are available to achieve this goal.[17]

The committee is convinced that a cutoff of fissile material production could be monitored with relative ease by using a combination of national technical means of intelligence and inspections of fissile material facilities. Such facilities could be placed under IAEA safeguards comparable to those in place in non-nuclear-weapon states; this would allow a global cutoff agreement to be nondiscriminating. If the cutoff were limited to the United States and Russia, less intrusive transparency measures would probably suffice, since the goal would be to detect militarily significant production in states already possessing substantial stockpiles of nuclear weapons.

[17] The Russian plutonium production reactors use aluminum-clad fuel, which the Russian government argues must be reprocessed because it cannot be stored safely. There are some questions about this argument: while some U.S. aluminum-clad fuel has been reprocessed for similar reasons (and problems have arisen with storage of some fuel), such fuel has been stored safely in water at the Massachusetts Institute of Technology, for example, for two decades. Even if this argument is accepted, however, two main options are available for cutting off plutonium production. The first is converting the reactors to use fuels that would not require reprocessing. The comparable U.S. N-reactor production facility at the Hanford reservation, for example, used zirconium-clad fuel similar to that used in commercial reactors, which can be stored safely, and can be used in the reactor for several times as long, producing much less spent fuel that requires storage. The second is shutting the reactors and providing alternative sources of power. This would require either new transmission capacity to carry power from elsewhere or the construction of new power plants (and possibly new gas pipelines). This latter option might be more expensive and time-consuming than the former, but would eventually have to be pursued in any case.

In 1992, in a letter cosigned by representatives of MINATOM and the Kurchatov Institute, the Russian government formally requested assistance from the United States in converting these reactors. After some internal discussion, the United States agreed to send a team to discuss the practicality of converting the reactors. Delays have been encountered on both sides, but as of late 1993, the pace of efforts in this regard appeared to be increasing.

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Adding It Up

As noted, such measures would work together synergistically. To undertake a militarily significant "breakout," a potential violator would have to deliberately leave large quantities of weapons or materials out of the initial declarations (or successfully produce both later in secret plants without detection); successfully falsify decades of operating records in a way consistent with the state of all the existing facilities; provide delivery vehicles to launch the weapons, in the context of the overlapping START verification regime; and so on. Each of these hurdles, while not insurmountable in itself, provides an additional risk of detection. The combination of measures would make the possibility of successful evasion acceptably remote.

INTERNATIONALIZING THE REGIME

Most if not all of the regime described above can and should be extended worldwide. The standards set in managing U.S. and Russian excess weapons and fissile materials can provide the base for improving management of these items throughout the world, and the opportunity to do so should be taken. As the Clinton administration's September 27, 1993, statement on nonproliferation policy put it, world stocks of fissile materials should be "subject to the highest standards of safety, security, and international accountability."[18]

Declarations of weapons holdings should be made by all the declared nuclear-weapon states, while declarations of fissile material holdings should ultimately include all states.[19] Such universal reporting of stocks of fissile material, which should include information on all imports and exports of fissile materials, would complement the information that the non-nuclear-weapon parties to the NPT are already required to give to the IAEA, providing a substantially firmer base for planning international fissile material management policy, which will remain an essential aspect of nonproliferation.

Similarly, as additional states come to participate in nuclear arms reductions, arrangements comparable to those described in this chapter for monitoring subtractions from their stockpiles and committing excess fissile materials to non-weapons use or disposal should be put in place.

Making a cutoff of production of fissile materials for weapons a global accord, as recently proposed, rather than solely a U.S.-Russian pact, would have particular significance, marking a major step forward in nonproliferation efforts. A global cutoff would establish the fundamental principle that it was no

[18] White House Fact Sheet, "Nonproliferation and Export Control Policy," September 27, 1993.

[19] At present it is probably not realistic to expect states that have not formally declared their nuclear weapons capability, such as Israel, India, and Pakistan, to declare the number of nuclear weapons available to them; hence declarations of nuclear weapons holdings would apply only to acknowledged nuclear-weapon states. These "threshold" countries are also likely to be reluctant to declare their holdings of fissile materials, but the regime should encourage them to do so.

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longer legitimate for any state to produce the essential ingredients of nuclear weapons, except for peaceful purposes under safeguards. If states such as Israel, Pakistan, and India could be convinced to accept such an agreement, it would cap their undeclared arsenals without requiring them to either acknowledge or roll back those arsenals immediately. Such a first step would go a long way toward limiting the potential for a nuclear arms race on the South Asian subcontinent.

At the same time, the stringent standards of security and accounting that should be set for storage and processing of excess fissile materials from weapons (see Chapter 5) should be extended to all civilian weapons-usable fissile materials worldwide. Such a step would significantly reduce the risks of diversion or theft of nuclear materials from civilian fuel cycles.

The IAEA secretariat and organizations in several countries are now working on concepts for such universal reporting and safeguarding of fissile materials.

MANAGING AND MONITORING DISMANTLEMENT

Current Practices

Dismantlement in the United States

In the United States, nuclear weapons are being dismantled at the Pantex plant in Amarillo, Texas, at a rate that has varied over the last several years, reaching 1,600 warheads in 1991 (see Table 4-1).[20] DOE is striving to increase this rate to roughly 2,000 per year. The United States plans to dismantle a large fraction of both its tactical and its strategic arsenals, though decisions on the number of weapons to be retained as inactive reserves remain to be made.[21]

The U.S. dismantlement rate is limited by the size of the available infrastructure and by a set of practical considerations, most of them related to the need to maintain applicable standards of protection for environment, safety,

[20] One type of weapon, the W-33, which did not include plutonium components, was dismantled at the Y-12 plant in Oak Ridge, Tennessee, rather than at Pantex. See U.S. Congress, General Accounting Office, *Nuclear Weapons: Safety, Technical, and Manpower Issues Slow DOE'sDisassembly Efforts*, GAO/RCED-94-9 (Washington, D.C.: U.S. Government Printing Office, October 1993).

[21] Recent Defense Department statements suggest that the inactive reserve—nuclear weapons that remain assembled, but are not among the 5,100 weapons slated to be in the future active U.S. nuclear force—may take on greater significance than it has had in the past. Undersecretary of Defense John Deutch, for example, recently told Congress that because problems with the weapons complex and the end of nuclear testing would leave the U.S. ability to produce new warheads "severely constrained," some warheads would be kept in the inactive reserve "to replace active weapons if necessary." Deutch argued that the inactive reserve "holds the Nation's only capacity for augmenting our significantly reduced active nuclear forces in response to a reversal in current geopolitical trends or the emergence of a new strategic threat." (See U.S. Congress, House Appropriations Subcommittee on Energy and Water Development, *Energy and Water Development Appropriationsfor 1994* Part 6, p. 1311.) The appropriate size and operational posture of the U.S. nuclear arsenal is being reexamined in new studies by the Defense Department and the National Security Council.

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and health. Dismantlement is conducted under carefully designed, preapproved, step-by-step procedures, which are time-consuming. The existing facilities and personnel are working close to capacity. Thus, significantly speeding the pace of dismantlement would require either hiring and training a substantial number of extra personnel, in order to add an additional shift at existing facilities, or building new facilities. Even hiring and preparing workers for an additional shift would take several years because there are extensive screening and training processes for personnel who are to handle nuclear weapons. Since, at the currently scheduled rate, planned U.S. dismantlements would be largely complete by the year 2000 in any case, such steps would not drastically shorten the remaining time to completion.

TABLE 4-1 Warhead Dismantlement in the United States

Fiscal Year	Numbers Retired and Disassembled
1980	535
1981	1,416
1982	1,360
1983	960
1984	860
1985	927
1986	574
1987	1,068
1988	510
1989	1,134
1990	1,056
1991	1,546
1992	1,274

SOURCE: U.S. Department of Energy, cited in U.S. Congress, Office of Technology Assessment, *Dismantling the Bomb and Managing the Nuclear Materials*, OTA-O-572 (Washington, D.C.: U.S. Government Printing Office, September 1993), p. 24.

The weapons components resulting from dismantlement are either stored, destroyed, disposed of as waste, or processed to recover valuable materials. The plutonium weapons components, known as pits, are currently being placed in intermediate storage at Pantex, while the highly enriched uranium components are being shipped to the Y-12 plant at Oak Ridge, Tennessee, where they can be stored or processed for use as nuclear fuel in naval or civilian reactors. High-explosive components are being burned in the open at Pantex, but environmental

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and public acceptance considerations may make it difficult to continue that practice.[22]

Dismantlement in Russia

In Russia there are four sites where weapons are assembled and can also be disassembled: Arzamas, Penza, Zlatoust, and Nizhnaya Tura. Information about Russian dismantlement rates is uncertain. Russian officials responsible for these programs have indicated that their dismantlement rate is somewhat greater than that of the United States. In public testimony, the Department of Defense has estimated that the current dismantlement rate in Russia is approximately 2,000 per year, comparable to the U.S. rate.[23] In both official and private discussions, Russian officials have indicated that rates as much as twice or even three times that of the United States could be attained (for example, the Central Intelligence Agency reports that the Russians have indicated a capability to dismantle 4,000-5,000 weapons per year, which the agency says it has no reason to doubt).[24]

Why Russian dismantlement is not currently proceeding at the maximum attainable rate is uncertain. Russian spokesmen have claimed that dismantlement rates are severely limited by available storage capacity for the fissile components of nuclear weapons. However, making existing storage sites available, possibly with modifications, in both the nuclear weapons complex and the military complex would provide adequate space (see Chapter 5).

The economic and budgetary turmoil in Russia appears to be one source of significant problems for dismantlement. Workers at some key nuclear sites, including those involved in dismantlement, have gone unpaid for months at a time and have threatened strikes. To the extent possible, the U.S. government should attempt to be helpful in ensuring that sufficient resources are available to accomplish critical tasks such as dismantlement. The planned HEU deal should be a step toward that objective, and additional options for providing financial or other incentives for dismantlement should be pursued.

Unlike the United States, Russia has assumed some formal obligations to dismantle nuclear weapons, which might be seen as seeds from which the broader transparency regime might grow. Commitments to dismantle weapons removed from certain states of the former Soviet Union are contained in some

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[22] For a more detailed account of current U.S. dismantlement practices, see U.S. Congress, Office of Technology Assessment, *Dismantling theBomb and Managing the Nuclear Materials*, OTA-O-572 (Washington, D.C.: U.S. Government Printing Office, September 1993).

[23] Ashton B. Carter, Assistant Secretary for National Security and Counter proliferation, Department of Defense, testifying at a hearing of the House Foreign Affairs Committee, "U.S. Aid to the Republics of the Former Soviet Union," September 21, 1993 (transcript, *FederalNews Service*). In Russia, unlike the United States, limited production of new nuclear weapons is also believed to continue.

[24] Testimony of Lawrence Gershwin, National Intelligence Officer for Strategic Programs, Senate Government Affairs Committee, February 24, 1993 (transcript, *Federal News Service*).

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of the accords reached in the framework of the Commonwealth of Independent States, in the negotiated letters accompanying the Lisbon Protocol, and in an agreement between Russia and Ukraine reached in April 1992, which contains detailed provisions for Ukrainian monitoring of the dismantlement of weapons removed from Ukrainian territory. Russian officials report that the latter agreement is currently being implemented and that, as of the spring of 1993, half of the tactical nuclear weapons removed from Ukrainian territory had been dismantled, with Ukrainian monitoring.[25] In addition, as currently conceived, the arrangements for the HEU purchase now in the final stages of negotiation and for U.S. funding of a fissile material storage site in Russia will both specify that the material involved must come from dismantled weapons (though measures to verify this will be limited or nonexistent). This creates an obligation to dismantle enough nuclear weapons during the 20-year period of the agreement to provide 500 metric tons of HEU.

Monitoring Dismantlement

With the exception of the monitoring called for under the Russian-Ukrainian agreement (and limited openness to the public at Pantex), no measures are in place that are specifically designed to increase the transparency of the dismantlement process. Such measures would increase the confidence of the parties to the current reductions accords, as well as the international community, that dismantlement is in fact taking place and that the denuclearization process is being securely managed.[26] Increased transparency for weapons dismantlement has thus far been resisted within the U.S. government and some sectors of the Russian government, for three reasons: (1) the need to protect sensitive weapons design information, (2) the urgency of proceeding with dismantlement, and (3) the costs of monitoring.

These objections have some merit; yet the process of introducing increased transparency measures need not significantly slow down the process of dismantlement, unduly compromise sensitive information, or break the bank. Moreover, as described above, there are compelling motivations for increasing transparency. Although the uncertainties concerning dismantlement rates are greater for Russia than for the United States, monitoring of dismantlement

[25] Interview with General Sergei Zelentsov (retired) and Colonel-General Vitali Yakovlev, former commander and current deputy commander, respectively, of the Russian military's 12th Main Directorate, in charge of nuclear weapons, Moscow, May 1993.

Ukraine has insisted that all weapons removed from its territory be dismantled, and Kazakhstan appears to take a similar position. Some weapons being withdrawn from Belarus, however, in particular the modern SS-25 mobile intercontinental ballistic missiles, may well be incorporated into Russian strategic forces.

Some Ukrainian officials continue to claim that the monitoring provisions of the April 1992 agreement have not been implemented, though others indicate that they are fully satisfied with these verification arrangements.

[26] As part of the broad regime outlined here, such increased transparency could begin before dismantlement as well, including, for example, monitored storage of excess weapons awaiting dismantlement.

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should be reciprocal, both because of the benefits of a reciprocal regime and because reciprocity would greatly improve the political acceptability of monitoring measures.

The best available means to monitor dismantlement without significantly compromising sensitive design information would be a variant of the perimeter-portal monitoring (PPM) system now in place to verify that missiles banned by the INF treaty are not being produced.[27] Under such an arrangement the disassembly facility would be securely fenced, with the exception of monitored entry and exit points. At the entry point, technical equipment could be used to verify that an entering object is a nuclear weapon. A variety of technical means to do so exist that could be used in a mutually supportive manner. The leading technique is x-ray radiography, which could be constrained (to the satisfaction of both the inspecting and the inspected parties) to ensure that the resolution of the image provided was good enough to verify that the entering object was a weapon, but not good enough to reveal the most sensitive design details. Additional methods include passive detectors to observe the radiation emitted by nuclear weapons and active detectors to observe the radiation emitted in response to interrogation by a particle beam, among others.[28] At the exit point of the facility, the material going out could be assayed for fissile material content (by methods external to the canisters containing the fissile components, to avoid inspection of the detailed dimensions of the components, which itself is classified information). Although the committee is persuaded that monitored dismantlement using such PPM methods can be made without compromising vital design information, it will be necessary to declassify some limited information that is now considered restricted data, such as radiation spectra from weapons.

Currently, assembly and disassembly of nuclear weapons take place in the same group of structures at Pantex. Similarly, it is the committee's understanding, based on discussions with Russian officials, that in Russia, each specific weapon type is assembled and disassembled in the same facility, although within those facilities, assembly and disassembly are segregated. In principle, perimeter-portal monitoring could simply be imposed on such joint assembly and disassembly facilities, thereby monitoring both dismantlement and assembly at the same time. Both incoming and outgoing weapons could be counted, with the difference being credited as disassembled weapons; the fissile material content of the weapons components leaving the PPM enclosure and going into safeguarded storage could be assayed after exit; and nonfissile components could be brought into and out of the facility in opaque containers, with the

[27] Under the INF treaty, the United States has a PPM installation at the Russian Votkinsk missile production facility, to ensure that prohibited SS-20 INF missiles are not produced there. The Russians have similar monitoring opportunities at a U.S. missile facility at Magna, Utah.

[28] For more details on portal monitors for identifying nuclear weapons, see Drell et al., op. cit.; and David Albright, "Portal Monitoring for Detecting Fissile Materials and Chemical Explosives," in Frank von Hippel and Roald Z. Sagdeev, eds., *Reversing the Arms Race* (New York: Gordon and Breach Science Publishers, 1990).

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monitors learning nothing about their contents except the basic fact that they did not contain substantial quantities of fissile material.

Alternatively, assembly and disassembly of nuclear weapons could be segregated (as they already are in Russia) in order to exclude assembly operations from monitoring or to impose different types of monitoring and levels of intrusiveness on the two operations. At the Pantex plant, some of the essentially identical structures used for assembly and disassembly could be devoted exclusively to dismantlement, and others exclusively to assembly. This would not require significant modifications of existing facilities, although it would probably come at some modest cost in operational efficiency.

If, as it appears, segregating assembly from disassembly would not impose substantial costs or delays, this would probably be the preferable approach, to ease the task of designing monitoring arrangements most appropriate to the degree of sensitivity of the activity being monitored. Information concerning the design of weapons types to be retained in active service, for example, may be more sensitive than the design of weapons being retired. The problem of protecting sensitive information related to the nonfissile components flowing into the assembly operation would be reduced. Similarly, if the sides agreed to tag particular weapons to be dismantled under an arms agreement, it would be considerably easier to determine that these specific weapons had been dismantled if intact weapons were not leaving the same facility. As noted above, however, if a regime is to be built that monitors the *net* subtraction of nuclear weapons from each side's arsenal, both assembly and disassembly will have to be subject to some form of transparency. The specifics of how the monitoring of dismantlement should be implemented are matters that must be subject to further internal consideration by each party and to bilateral negotiation.

MANAGING DISMANTLEMENT FOR ENVIRONMENT, SAFETY, AND HEALTH

Protection of the environment, safety, and health must be a critical part of the dismantlement effort. The most obvious and compelling safety issue is ensuring against the possibility of a nuclear explosion. Addressing this problem requires great care, including disabling warheads prior to disassembly, to prevent a nuclear yield. A possibility of conventional explosions that might cause plutonium contamination remains, however. The "Gravel Gerties" used for dismantlement are designed to contain such explosions, limiting damage and contamination to the interior of the particular dismantlement module itself. Nevertheless, precautions must be taken to ensure against such explosions; none has occurred in the decades of operation at Pantex.

Other ES&H issues involved in dismantlement include worker exposures to radioactive and toxic materials; transport of hazardous materials to and from the facility; disposal of hazardous materials on-site (including open burning of explosives from disassembled weapons at Pantex, which has been the focus of

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particular public concern); criticality safety; and possible safety issues associated with storage of weapons and fissile materials (such as the possibility of an aircraft crash on the storage facility). All these issues are being addressed, to varying degrees, but dismantlement will never be a risk-free endeavor. The ES&H dangers involved in dismantlement, however, are far less severe than those of many other U.S. (and Russian) nuclear weapons complex activities, particularly since there is no actual processing of plutonium or other radioactive materials. Considering the methods used for dismantlement in the United States, it is the committee's judgment that there is little doubt that dismantling weapons and storing or disposing of the resulting materials is safer overall than storing the assembled weapons indefinitely.

Public support for weapons complex operations, however, can be secured only by providing greater openness and public participation in decision making. In the new environment in which DOE finds itself, such participation is required if dismantlement is to continue at projected rates. DOE is making progress in setting up mechanisms to meet these needs. Nevertheless, public involvement is currently embryonic and in need of further development.[29]

RECOMMENDATIONS

The committee has deliberately included consideration of both dismantlement and declarations in a single chapter, since both are critical to the creation of a meaningful future control regime encompassing all nuclear weapons and weapons-usable fissile materials. The committee recommends that:

- The United States and Russia should make formal commitments that specific quantities of fissile material from dismantled weapons (representing a very large fraction of those materials) will be declared excess and committed to non-weapons use or disposal. Storage and disposition of these materials should be subject to agreed standards of accountability, transparency, and security. The standards for accountability and security should approximate as closely as possible the stringent standards applied to stored nuclear weapons.
- The United States should negotiate with Russia to create, through a step-by-step process, a broad regime under which each side's stocks of nuclear weapons and fissile materials would be declared and monitored, and the size of both stocks would be verifiably reduced over time in line with current reductions in deployed delivery systems. This regime would include, in addition to the fissile material steps mentioned in the previous recommendation:

1. a system of mutual declarations of total inventories of nuclear weapons and of fissile materials in civilian and military inventories;

[29] See U.S. Congress, Office of Technology Assessment, op. cit.

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2. measures designed to increase confidence in the accuracy of the declarations, and the transparency of each side's nuclear weapons production complexes, including physical access to production facilities and production records for fissile materials;
3. a monitored cutoff of production of HEU and plutonium for weapons. If necessary, the United States should be willing to provide limited funding to assist Russia in the measures necessary to cut off plutonium production; and
4. an agreement providing for perimeter-portal monitoring of dismantlement facilities, counting warheads entering these facilities and assaying the fissile material that leaves. If the *net* subtractions from each side's stockpile are to be confirmed, some monitoring of warhead assembly will be required as well.

- Information concerning the total stockpiles of weapons and fissile materials, and those weapons characteristics necessary for external monitoring, should be declassified as part of this transparency regime. Appropriate reviews to prepare for such declassification should be initiated promptly.
- Russia and the United States should dismantle their retired warheads as expeditiously as is practical, consistent with protection for the environment, safety, and health, and cost-effectiveness.

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5

Intermediate Storage

Following dismantlement, described in the previous chapter, a substantial period of intermediate storage of the fissile materials will be required, as none of the plausible options for long-term disposition can significantly reduce the stock of excess plutonium for more than a decade. What happens during that period is therefore of critical importance.

As a central part of managing this intermediate storage, the United States and Russia should rapidly make formal commitments that:

1. specific, agreed amounts of fissile materials from dismantled weapons will never again be used for weapons; and
2. verification of non-weapons use or disposal will be established in both countries through a combination of bilateral and international safeguards over the storage sites for these materials.

Such steps to subtract fissile materials from the stock available for weapons, with monitoring, would be fundamental parts of the regime outlined in the last chapter, serving the same objectives of reducing the risks of theft and of breakout, and of strengthening arms reduction and nonproliferation.

At the same time, it is not just these *excess* materials that pose dangers. Urgent steps are needed to improve accounting and security for *all* fissile materials in the former Soviet Union, and for the United States and other countries to provide assistance in that regard. Stringent safeguards and physical security for fissile materials from dismantled weapons in the United States and Russia can set a standard for a regime for improved management of such materials in civilian use throughout the world.

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PRESENT ARRANGEMENTS AND PLANS FOR PLUTONIUM STORAGE

Currently, in both the United States and Russia, as weapons are dismantled the resulting fissile materials are stored in existing facilities, some at the dismantlement site and some elsewhere, in the form of intact weapons components. Neither country has yet determined how much of these fissile materials will be kept as reserves and how much declared "excess" to military needs—a critical policy decision.[1] No monitoring or transparency measures relating to storage or use of these fissile materials are yet in place. In an important initiative on September 27, 1993, however, the United States announced that it would voluntarily place materials it determined to be excess under International Atomic Energy Agency (IAEA) safeguards. Russia has expressed willingness to do the same, but no negotiations on this subject are yet under way.[2] No decisions have yet been made concerning what specific materials would be covered by such an arrangement; at what facilities they would be located; or how plutonium in pit form could be placed under safeguards, without compromising sensitive nuclear weapons information. Discussions of more limited transparency measures associated with both the highly enriched uranium (HEU) deal and the planned U.S. assistance in construction of a fissile material storage site in Russia are continuing.

The United States

Pits at Pantex

The U.S. nuclear weapons assembly and disassembly facility, the Pantex plant near Amarillo, Texas, has recently been pressed into service for "interim" storage of plutonium. Until 1989, when the plutonium processing facility at Rocky Flats, Colorado, was shut down because of safety and environmental problems, the plutonium pits from nuclear weapons were sent from Pantex to Rocky Flats to be processed into new pits for new weapons. Since Rocky Flats' closure, these shipments have been cut off, and pits from dismantled weapons have been stored in growing numbers in preexisting bunkers (called "igloos") at the Pantex facility.

The HEU components of dismantled weapons continue to be shipped from Pantex to the Y-12 plant at Oak Ridge, Tennessee, where they were produced,

[1] The U.S. Department of Energy has recently declassified the guarded statement that "up to" 50 tons of plutonium "will (or may)" become excess. No similar announcement has been made concerning HEU since some of the HEU from dismantled weapons will be used to fuel naval and research reactors. See Louis R. Willett, Deputy Director, Office of Weapons and Materials Planning, Defense Programs, U.S. Department of Energy, "Excess Fissile Materials," presented at the Annual Meeting of the American Power Conference, Chicago, Illinois, April 13-15, 1993.

[2] Russian delegation statement to the United Nations Conference on Disarmament, August 17, 1993.

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and where they can be stored or processed and fabricated into reactor fuel. While the majority of the HEU stored in the weapons complex is located at Y-12, HEU is present at several other sites as well.

As dismantlement continues, pit storage at Pantex will soon reach its limits, unless storage arrangements are modified.[3] The Department of Energy (DOE) and the contractor operating Pantex have developed a plan to increase pit storage capacity at the site to 20,000, by using some additional igloos not previously used for pit storage, and by modifying the stacking arrangements within the igloos to increase the number of pits stored in each one. This plan, if approved, would provide adequate interim storage space for all of the plutonium from weapons that the United States currently plans to dismantle. DOE's Environmental Assessment of this plan has drawn some criticism from the state government and the public in the area surrounding the plant, but it appears likely that the plan or a variant of it will ultimately be approved. It appears that storage of additional pits at Pantex will pose few risks beyond those of the existing pit storage operation —lower risks than would be posed by continued storage of weapons without disassembly. Neither the pits nor the concrete igloos at Pantex are likely to deteriorate significantly over the next few decades. In a technical sense, therefore, storage in the material's present form at the current site could be continued for that period without undue risk, provided that an adequate program to monitor the pits' status and respond to any problems was maintained.

State and local governments and the local populace, however, were assured by DOE in the early 1990s that interim storage in the existing Pantex facilities would last for only 6-10 years. No decision has yet been made on a site for longer-term storage (see below); Pantex is one of several candidates still under consideration. DOE has recently taken a number of initiatives to expand public participation in decisions regarding operations at the Pantex site. The committee believes that such steps toward providing genuine public participation will be essential in securing public acceptance for whatever storage approach is ultimately chosen.

Plutonium in Other Forms

Many tons of military plutonium not incorporated in weapons are stored at sites elsewhere in the U.S. weapons complex, including Rocky Flats, Hanford, Los Alamos, and Savannah River. This plutonium ranges from material that could be rapidly incorporated into weapons, such as relatively pure metal and oxides, to material that would be rather difficult to recover, such as plutonium in liquid residues from processing operations or discarded equipment and

[3] U.S. Department of Energy, Albuquerque Operations, Amarillo Area Office, *Environmental Assessment for Interim Storage of PlutoniumComponents at Pantex*, DOE/EA0812, Predecisional, December 1992.

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clothing contaminated with plutonium. For some of these materials, planned cleanup efforts include recovery of plutonium in relatively pure form, whereas others will be discarded as waste. Given the substantial surplus of pure weapons plutonium, the recovery of plutonium from these materials is justified only if it is judged to provide a net benefit—for security against theft or for environment, safety, and health (ES&H)—worth the cost of recovery.

Future Plans

DOE is developing concepts for a new plutonium storage facility, which would replace storage at Pantex and at all of the other sites where military plutonium is currently stored. This facility, as currently conceived, would be capable of holding plutonium in any solid form. It would have a modular design, allowing expansion to hold as much plutonium as ultimately required, at a capital cost estimated at $1 billion or more.

In DOE's concept, the nuclear weapons complex's plutonium processing, fabrication, and R&D activities would be located at the same site. DOE is considering the possibility of storing all HEU there as well. Five sites are under consideration: Pantex, the Idaho National Engineering Laboratory (INEL), Savannah River, Y-12, and the Nevada Test Site. DOE hopes to make a "record of decision" on this facility in late 1994, as part of its Programmatic Environmental Impact Statement (PEIS) for the reconfiguration of the U.S. nuclear weapons complex—known as "Complex-21"—and to open the first module in 2001.[4]

DOE advocates of a new storage facility believe that consolidation of plutonium at this central facility is needed to meet modern standards of ES&H protection at an acceptable cost. Despite the substantial capital cost, they argue that building such a facility would in fact save money in the long run. Both excess material and material that remains in reserve for military purposes would be stored at the same site, although the United States does not intend to place reserve materials under international safeguards. In principle, reserve materials could be stored in a separate module or storage area subject to different transparency arrangements.

The principal alternative to building such a consolidated storage facility is to upgrade existing plutonium storage facilities. Upgrades designed for least-cost solutions to specific ES&H problems might offer a cheaper alternative to the facility envisioned by DOE. DOE's formal environmental assessment of these alternatives, which will include estimates of cost and effectiveness, is not complete, and this committee could not undertake such an assessment. The committee therefore offers no judgment on the merit of these options, although

[4] See *Federal Register*, July 23, 1993, pp. 39528-39535. The Complex-21 effort is a broad DOE plan to reconfigure the U.S. nuclear weapons complex to mitigate the environmental damage of the Cold War period and adjust to new, post-Cold War missions and requirements.

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there are potential advantages in having all U.S. military fissile materials located at a single site for the kind of safeguards regime described below.[5] Even if a way could be found to carry out disposition of the excess plutonium in pits at Pantex quickly, it would not necessarily obviate the need for such new facilities or upgrades, given the large amount of plutonium stored elsewhere in many forms.

Russia

Storage of Weapons Components

As mentioned in Chapter 4, Russia is believed to be dismantling nuclear weapons at four sites. As in the United States, plutonium and HEU in weapons components resulting from this dismantlement activity are believed to be stored both at the dismantlement facilities and at sites where the fissile materials were produced. Little is known about the safeguards and security applied to these fissile materials, or to other fissile materials in the Russian nuclear weapons complex or in civilian use (see Chapter 2 for a more extensive discussion). Similarly, little is known about Russian standards and practices for ES&H.

The Russian government has asserted that lack of adequate storage space is a major bottleneck in its dismantlement plans, and that if dismantlements continue as planned and no additional space is provided, it will run out of storage space by 1997.[6] If, however, Russia used both storage facilities controlled by the Ministry of Defense and those controlled by the Ministry of Atomic Energy (perhaps with some modifications), more than adequate storage space would be available. A parallel situation exists in the United States, where the Department of Defense controls facilities that might be suitable, with some modifications, for storing DOE-controlled fissile materials. Obstacles to the provision of adequate storage in Russia may therefore be more bureaucratic than physical.

Nevertheless, the United States has agreed to provide assistance in designing and equipping a large fissile material storage facility in Russia. $90 million in Nunn-Lugar assistance funding has been allocated for this purpose to date. The committee supports construction of a facility designed to consolidate all these excess weapons materials, with U.S. participation, since this would facilitate security and international monitoring. Negotiations concerning this facility are still in flux, however, and recent developments may call some of the goals

[5] In principle, concentrating all U.S. fissile materials at a single site might raise concerns about the site's vulnerability to attack. But in the United States, such sites are likely to be extremely well protected against plausible conventional attacks, and in the event of nuclear attack, having several sites would offer little reduction in overall vulnerability of the stock. Thus, this concern should not be a major factor in decisions concerning storage of the nation's stocks of fissile materials.

[6] See Joseph E. Kelley, U.S. General Accounting Office, *Soviet NuclearWeapons: U.S. Efforts to Help Former Soviet Republics Secure andDestroy Weapons*, statement before Senate Committee on Governmental Affairs, March 9, 1993, GAO/T-NSIAD-93-5.

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of this assistance into question.[7] Russian officials had hoped to break ground on the facility in the first half of 1994 and to have it operational just at the time they project existing space will run out in 1997.[8] If a new site has to be chosen, the U.S. government should urge the Russian government to select one of the major Russian weapons dismantlement facilities, to minimize the transportation of fissile materials and the associated security risks.

Under current plans, the material in this facility will be stored primarily as weapons components. Russia has assured the United States that the material to be stored in this facility will never again be used in weapons. Discussions of transparency arrangements to verify this commitment are continuing. Neither a permanent U.S. inspection presence nor IAEA safeguards are currently planned, however. Nor is there yet any agreed arrangement for safeguards on the material after it is withdrawn from the facility for civilian use or disposal. In addition, standards and procedures for security for the site are not yet agreed and may be handled unilaterally by Russia.

Plutonium in Other Forms

Russia also has tens of tons of plutonium not incorporated in weapons stored in various forms at several sites in its weapons complex. Little is known about the quantity, condition, or security of this material. In addition, Russia has roughly 25 tons of civilian separated plutonium stored at the Mayak reprocessing complex. In early 1991, a Soviet interagency report concluded that at this site, "the current method of storing plutonium does not correspond to world practice and presents security concerns."[9] Russia also has plutonium and HEU at a number of civilian sites for research purposes. Urgent steps should be taken to improve security and accounting of fissile materials at all of these sites (see below).

[7] While the Russian Ministry of Atomic Energy has suggested locating the facility at Tomsk—the site of several aging plutonium production reactors and a major plutonium reprocessing facility—local and regional authorities have objected. Opposition grew after the explosion of a nuclear waste tank there in early 1993. There are now reports that the Tomsk authorities will allow only a storage site for the materials already stored there, so that the facility would provide no additional space for materials from weapons now being dismantled, and the objective of consolidating all excess plutonium and HEU at a single site would be compromised. Further developments could change this outcome. It would be difficult to justify spending $90 million of the available Nunn-Lugar funds if the facility were to serve only as a replacement for existing storage capacity at a single site.

[8] See Kelley, op. cit.; and U.S. Department of Defense, *QuarterlyReport on Program Activities to Facilitate Weapons Destruction andNonproliferation in the Former Soviet Union* (Washington, D.C.: U.S. Government Printing Office, September 29, 1993).

[9] *Report by the Commission for the Investigation of the EnvironmentalSituation in the Chelyabinsk Region*, January 1991, cited in Oleg Bukharin, *The Threat of Nuclear Terrorism and the Physical Securityof Nuclear Installations and Materials in the Former Soviet Union* (Monterey, Calif.: Center for Russian and Eurasian Studies, Monterey Institute of International Studies, Occasional Paper No. 2, August 1992), p. 7.

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TECHNICAL ISSUES

In general, plutonium stores are large, highly secure vaults (or a series of smaller vaults, as in the case of the Pantex igloos), protected by various physical security technologies (barriers and the like) and substantial guard forces. Within the vault, plutonium is generally stored in sealed canisters. These canisters reduce radiation exposure from the plutonium; reduce the plutonium's exposure to the environment; ease the task of accounting for the material, allowing monitors to simply count the canisters and check their seals (an approach known as "item accountancy"); and are usually designed to keep the pits or other units of plutonium far enough apart to prevent any accidental nuclear chain reaction ("criticality"), regardless of the number or configuration of the canisters.

Criteria for Plutonium Storage

What criteria should govern the design and operations of such sites? First, there must be assurance of adequate protection for the environment, and for the health and safety of both workers and the surrounding community—a matter of increasing political attention in both Russia and the United States. Storage facilities must be designed to provide reasonable assurance that there will be no significant releases of plutonium into the environment, not only under normal operating conditions, but in the case of plausible attacks or accidents (for example, earthquakes, fires, floods, and plane crashes). Similarly, workers' exposures to hazardous radiation within the facility must be minimized. Plutonium in storage must be arranged so that it can never be in a critical configuration. There must be adequate dissipation of the decay heat given off by the material. Any changes in the stored plutonium that might require further processing, or any deterioration of the containers or storage conditions, should be detectable. (Periodic, rather than continuous, checks for this latter purpose are adequate.)

Second, sites must be secure against theft or diversion, by "insiders" or "outsiders." They should therefore have effective material control and accounting systems for all stored materials in whatever form, as well as appropriate physical security.

The form in which the plutonium is stored (pits, metal ingots, and oxides are among the main possibilities) has a substantial effect on the details of the design of the facility. Some additional criteria are necessary to judge the optimum form of plutonium for storage. Criteria for this purpose include ES&H issues; proliferation risks; breakout risks; effects on arms control and nonproliferation; the risk of compromise of classified information; the forms needed for planned long-term disposition; and the costs, timing, and availability of facilities.

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Classes of Plutonium Storage Facilities

The criteria for safe and secure storage of plutonium can be met to varying degrees by facilities of several levels of sophistication. The facilities at Pantex represent the simplest end of the spectrum: they are simple above-ground igloos, with no electricity, only natural cooling, and no built-in measures for material control. This very simplicity has advantages, as there is little that can go wrong. Security, for example, is based not only on the presence of guards and response forces, but on the fact that the forklift required to lift the igloos' 40-ton doors could not pass unnoticed across the open desert. On the other hand, this simplicity also means that there are few provisions for mitigating the consequences of potential accidents, such as plutonium contamination within the igloo. Workers' exposures to radiation in the process of operations inside the igloos (such as taking inventory) are not insignificant and would increase under the plan to store additional plutonium pits there. Automation and robotics are being pursued to reduce these hazards.

As currently planned, the storage facility to be built in Russia would be considerably more complex. In designs that were current as of late 1993, the entire storage area would be underground; there would be complex electronic systems to support physical security and material control and accounting; and there would be a powered cooling system to remove the heat generated by tons of plutonium. Other advanced features are planned as well.[10]

The storage facility envisioned by DOE for the United States would incorporate the features of the Russian facility, and would also have an extensive on-site analysis and processing capability, making it still more advanced—and expensive.

Forms of Plutonium for Storage

Each of the criteria for forms of plutonium just mentioned are considered below in turn:

ES&H, Costs, Schedules, and Facility Availability

Storage as pits is the quickest, lowest-cost means to achieve safe and environmentally benign storage of plutonium from dismantled weapons. Leaving the pits in their current form during intermediate storage would postpone whatever costs, hazards, and wastes would be incurred in changing them to other forms. Although plutonium metal is usually prone to oxidation, in a pit the plutonium

[10] The United States has suggested to the Russian government that if adequate storage is a major bottleneck to dismantlement, quickly building simple storage such as that at Pantex might be a better approach than building a sophisticated facility that cannot be opened until 1997. Russian representatives, however, have strongly favored the more complex facility, saying that the simpler facilities would have to be replaced later by more advanced ones in any case.

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is sealed within a cladding of another metal such as steel. While plutonium is known to change over time, pits have proved remarkably stable over the several decades of experience with them in the United States, and one can have substantial confidence that with few exceptions they will remain stable for decades to come. In rare instances, however, problems may develop, such as air leaking into the pits so that the plutonium inside oxidizes. Periodic monitoring is thus essential.

No facility with the capability to change pits to other forms on the required scale is currently operating in the United States, although existing facilities at Rocky Flats, Los Alamos, Savannah River, and Hanford might be used if modified or reopened. Promising new procedures for conversion of pits to other forms, while minimizing waste and worker exposure to radiation, are under development at the national laboratories, and this work should continue.

Pits might be mechanically deformed (squashed) to lower the risk that they would be reassembled into weapons. Deformation of pits might compromise the pit cladding, increasing the risk of oxidation or other instabilities in the material. If deformation was considered desirable, the pit might be enclosed in a sealed envelope of a ductile material, such as aluminum, before deformation took place, to isolate it from the environment. (Such an envelope might also be useful in handling pits damaged as a result of normal operations). Conceptually, deformation operations using such envelopes appear relatively simple, and it would seem possible to carry them out even at locations such as Pantex that lack a genuine plutonium handling capability. A complete safety analysis would be required to assess this judgment, however.

Proliferation Risk

Plutonium in any relatively pure form poses similar proliferation risks (except, of course, in the form of an assembled nuclear weapon, in which case the risks are substantially greater).[11] Weapons can be made from the material without the need for chemical processing, whether it is in pits, metal ingots, alloys, or oxides. Building an explosive from oxide would require more material and would be somewhat more complicated; a sophisticated proliferator might choose to process the oxides into metal before use. A proliferator who managed to acquire plutonium stored in pit form could use it to fabricate a weapon that would generate a nuclear yield, even if the proliferator's explosive design were not well matched to that originally designed for the particular pit. Mechanically deforming the pits might not be effective in reducing this risk (although it would have some impact on the rearmament risk, described below). Having a pit available (rather than, for example, a metal ingot of plutonium)

[11] It is assumed here that all forms of plutonium would be stored in large, sealed canisters, so that differences in the potential for diversion of small quantities of material over time are not significant.

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would simplify weapons manufacture somewhat, but the most difficult steps in producing a weapon would remain.

Some Russian and U.S. officials have proposed blending excess weapons-grade plutonium with separated reactor-grade plutonium to create a material of intermediate grade for storage. As described in Chapter 1, however, although the increased neutron background, heat, and radioactivity from reactor-grade plutonium would complicate the job of making nuclear explosives from such a material, the reduction in proliferation risk would be small. Moreover, there are no significant stocks of separated civilian plutonium available for this purpose in the United States, and in either the United States or Russia, substantial processing would be required. Therefore this is not a promising approach to reducing the security risks posed by storage of weapons-grade plutonium.

In short, all forms of separated plutonium are hazardous, and proliferation risk alone cannot be used to discriminate easily among them.

Breakout Risk

The rearmament risk is greatest for storage of unmodified pits; all of the other forms pose roughly the same risks. With pits and HEU components still available, weapons could be reassembled relatively rapidly if other components were available or could be produced quickly. The delay imposed on a possible rearmament program by having to refabricate pits, however, would probably be measured only in months, and might not be a limiting factor when compared to the other tasks involved in a large-scale rearmament program—provided that facilities for pit fabrication were available. Moreover, an argument can be made that a nation contemplating a major breakout from existing treaties would want to build new weapons using new pits, specially designed to gain some military advantage; in that case the availability of the old pits would be irrelevant.[12]

Mechanical deformation would address the greater rearmament risk posed by storage of pits. To be reincorporated in modern weapons, the deformed pits would then have to be refabricated, making the crushed pit similar in rearmament risk to other storage forms. The ES&H issues raised by deformation have been described above.

Currently, the U.S. facility for pit fabrication at Rocky Flats is closed, and other available capacity is limited. Russia does not appear to face similar limitations. Thus, if pits were deformed or converted to other forms for storage, Russia might be able to rebuild its weapons more rapidly than the United States.[13]

[12] It is technically possible, however, to build new-design weapons around old-design pits, perhaps with some compromise in capabilities of the new weapons.

[13] It should be remembered, however, that a political environment in which a large-scale illegal rearmament program might be seriously contemplated by either side would be quite different from today's environment, probably more comparable to the darkest days of the Cold War. In such an

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Arms Reduction and Nonproliferation Regimes

Keeping fissile materials in the form of weapons components may be perceived politically as keeping open an option for quick rearmament, whether or not that is actually the case. This could potentially compromise U.S. credibility in the context of ongoing arms reductions, of extending and strengthening the Non-Proliferation Treaty (NPT), and of bringing other nuclear-weapon states into the reduction regime. Such perceptions provide another reason to consider measures such as deformation of pits. Putting the stored material under safeguards should also mitigate this problem significantly.

Compromise of Classified Information

Fissile materials in the form of weapons components contain classified weapons design information. Currently, a wide variety of information concerning weapons components is classified, although as noted in Chapter 4, a substantial amount of this information could be declassified without compromising U.S. security. Combining foreign inspection with the need to protect classified information is simplified by the fact that pits are stored in opaque canisters. Techniques for accurately measuring the amount of plutonium from outside the canister are available.

Whatever choice of storage form is made for the future, much of the plutonium from dismantled weapons will remain in pit form for years to come, simply because of the sheer scale of the task of converting tens of thousands of pits to other forms. It is therefore critical that any arrangement for safeguarded storage be at least *capable* of handling plutonium in pit form. Otherwise, a large fraction of the excess plutonium would remain outside the monitoring regime for a considerable period (see recommendations below).

Forms for Long-Term Disposition

Ultimately, for most long-term disposition options, the plutonium would have to be processed from pits to other forms. Thus, storage as pits would only *postpone* the ES&H issues and costs of processing. If the plutonium is to be used as an oxide fuel in reactors, for example, it must ultimately be converted to oxide, and near-term conversion to oxide form might be desirable. But that requires a definite decision on disposition options: if the material had been converted to oxide and later a decision was made to use it in metal form as fuel for fast reactors, for example, an expensive reconversion would be necessary.[14]

emergency, in response to a major Russian buildup, it should probably be assumed that a way would be found to open or modify U.S. facilities.

[14] If a definite decision was made to produce a particular type of fuel from the plutonium, there would be some advantages in fabricating the fuel sooner rather than later because highly radioactive americium-241 builds up in the material over time through the decay of plutonium-241 (Pu-241), increasing the difficulty of handling the material. In weapons-grade material, however, the percentage

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Recommendation

Given that no definite decisions on disposition of excess plutonium have yet been made, and given the near-term safety and environmental advantages of continued storage as pits, the plutonium should continue to be stored as intact pits for now. Deformation of these pits and perhaps other steps to reduce the rearmament risk should be given serious consideration, and should be undertaken if they can be accomplished at relatively low cost and ES&H risk. Once definite disposition options have been chosen, the plutonium should be converted expeditiously to whatever form is required as part of the disposition process.

Costs of Plutonium Storage

The cost of plutonium storage spans a wide range. In the commercial market, civilian plutonium reprocessors typically charge $2-$4 per gram per year for storage of separated plutonium. Storing 50 tons of plutonium for a decade, for example, would therefore cost $1-$2 billion. Actual costs may differ from fees charged in the market, however, and could differ markedly depending on circumstances.

At the Pantex site, most of the facilities in which plutonium is to be stored would otherwise be standing empty. Since Pantex is a major nuclear weapons facility, stringent security measures would be needed even if little plutonium were stored there. Thus, the net additional cost of storing plutonium at Pantex is minimal, and what additional costs there are (such as the cost of taking inventories and monitoring the status of the material) relate only weakly to the amount of material stored. A fixed number of dollars per gram is therefore not an appropriate measure in this case.

Only plutonium in pits is stored at Pantex. Storage of plutonium in less stable forms, such as the scrap and residues stored elsewhere in the U.S. nuclear weapons complex, may be substantially more expensive in some cases, particularly if processing is required.

At a site dedicated solely to fissile material storage, which both the United States and Russia now envision building, all the capital and operating costs should be allocated to the storage mission, thereby raising costs substantially above those at Pantex. The $90 million that the United States plans to provide for the Russian storage site does not include the costs of actually building that facility; its total capital cost will be in the range of a few hundred million dollars, while the cost of the envisioned U.S. facility may be a billion dollars or more. Operating costs for security, safeguarding, and other purposes would probably amount to a few tens of millions of dollars per year (less in the Russian

of Pu-241 is so small that the problem is relatively limited. This problem is much more significant for reactor-grade plutonium, with its much larger quantities of Pu-241, which must generally be fabricated within a few years after reprocessing or be processed again to remove the americium.

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case, where labor costs are lower). Such operating costs, although significant, do not in themselves create any great urgency for pursuing long-term disposition. As discussed in Chapter 6, it is the security risks and political disadvantages of storing the material indefinitely in readily weapons-usable form that create the primary incentive to move expeditiously to long-term disposition.

INSTITUTIONAL ISSUES

The committee considered a variety of institutional arrangements for plutonium storage, including options such as continuing current practices without change; adding additional bilateral transparency measures; setting up a new international group to fund and manage an internationally managed plutonium repository; setting up IAEA safeguards similar to the long-discussed "international plutonium storage" (IPS) concept; purchasing the plutonium and possibly shipping it elsewhere, as in the case of the HEU deal; and others.[15] These approaches generally differ in their assignment of particular responsibilities: Who (if anyone) monitors dismantlement of weapons? Who monitors or safeguards the plutonium? Who provides physical security for the plutonium? Who owns the plutonium? Who manages the storage site? Who makes decisions concerning withdrawals from the storage site, and use or disposal of the plutonium? Where is the plutonium located? What incentives might be offered to Russia, financial or otherwise, to place plutonium into such an arrangement, and by whom? Who pays for the scheme (including any financial incentives)? Different responsibilities might be assigned to different parties, as shown schematically in Table 5-1.

A New Regime for Secure, Safeguarded Storage

In sorting through these options, the committee emphasized the need to move quickly, given the current pace of events in the former Soviet Union. The critical task is to build rapidly on current operations, with as little disruption to the process of dismantlement and storage as possible, while meeting as many of the criteria outlined in this chapter and Chapter 3 as possible.

The committee recommends the following measures for intermediate storage of excess fissile materials, all of which are elements of the broader regime discussed in Chapter 4:

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[15] For discussions of some of the institutional approaches to storage, see, for example, Graham Allison, Ashton B. Carter, Steven E. Miller, and Philip Zelikow, eds., *Cooperative Denuclearization: From Pledgesto Deeds*, CSIA Studies in International Security No. 2 (Cambridge, Mass.: Center for Science and International Affairs, Harvard University, January 1993); and Lawrence Scheinman and David A.V. Fischer, "Managing the Coming Glut of Nuclear Weapons Materials," *Arms Control Today*, March 1992.

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TABLE 5-1 Selected Possible Institutional Options for Intermediate Storage

	Approach			
Function	A	B	C	D
Dismantling—monitored?	National No	National Yes—bilateral	National Yes—bilateral	National Yes—international
Ownership/custody	National	National	National	International
Financing	National	National	Bilateral	International
Custody/physical security	National	National	National	International
Monitoring	None	Bilateral	IAEA	IAEA
Location	National	National	National	IPS
Incentives	None	None	Assistance for storage	International purchase

1. *Formal Commitment to Non-Weapons Use:* Although some weapons and weapons components will inevitably be kept for reserves and stockpile support, the United States and Russia should explicitly commit a very large fraction of the fissile materials from dismantled weapons to non-weapons use or disposal. They should agree on the specific amounts to be committed to non-weapons use, and on the amounts of material that will remain in their military stockpiles in deployed weapons and reserves.
2. *Safeguarded Storage and Disposition:* This formal commitment should be verified by monitoring the sites where the excess fissile materials are stored. This monitoring would initially be imposed at existing sites (with commitments for similar arrangements at future sites); it would cover material either in its existing form (including intact weapons components) or in modified form. In the case of material in the form of weapons components, fissile materials would arrive at the storage site in tagged and sealed containers from dismantlement facilities. To avoid revealing design details, the material would be assayed from outside the canister, without the monitors ever seeing the components themselves. This would provide high safeguards confidence, without compromising information beyond the amount of fissile material in the components.[16] They

[16] See, for example, Thomas E. Shea, "On the Application of IAEA Safeguards to Plutonium and Highly Enriched Uranium from Military Inventories," *Science and Global Security*, Vol. 3, 1992, pp. 223-236. The concept of relying entirely, after an initial assay, on counting the sealed canisters and ensuring they had not been tampered with was recommended even for civilian plutonium by an IAEA expert group, which urged that "no verification activities other than item accounting and seal verification should occur within the store." See Charles van Doren, "Toward an Effective International Plutonium Storage System," U.S. Congressional Research Service, November 1, 1981, p. 46.

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would then be stored in secure vaults, with monitoring equipment and human monitors ensuring that the canisters were not tampered with or removed without authorization.

3. *IAEA Role:* In the interest of speed, storage monitoring might initially be a bilateral U.S.-Russian effort. It is important, however, to bring the IAEA into the process rapidly. For the near term, storage facilities should remain nationally owned and controlled, with the IAEA being given, in effect, a "subcontractor" role, monitoring the amount of material in the storage site and safeguarding any material removed from the site to verify the commitment to non-weapons use or disposal. Such safeguards would be an application of existing safeguards, rather than a fundamentally new system. Some bilateral monitoring effort would probably continue as well, particularly if monitoring were called for in especially sensitive areas.

There are several reasons why the IAEA is the most suitable organization for this role. Compared to a strictly bilateral approach, an IAEA role would garner more political support from key parties outside the United States and Russia, particularly non-nuclear-weapon states. The IAEA, with its experience in safeguarding large civilian stores of plutonium, has the expertise to carry out the task. Given sufficient resources, it could readily assemble new talent as required. If the United States and Russia requested such an IAEA role, the IAEA's Board of Governors is likely to approve, and safeguards could be set up expeditiously. Setting up an international group other than the IAEA might cause substantial delays.

President Eisenhower's "Atoms for Peace" speech in 1953, which first proposed an IAEA, envisioned the agency fulfilling exactly this role of overseeing material transferred from military stocks for peaceful purposes. The IAEA's statute provides for such a role, and IAEA Director-General Hans Blix has volunteered the agency's services for this purpose.[17] In these circumstances, creating

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Even safeguards arranged through the IAEA could in principle be limited to personnel from nuclear-weapon states if this were considered necessary, as Shea points out. Safeguarding of centrifuge enrichment plants is already limited to personnel from countries possessing centrifuge technology, to avoid spreading the technology through safeguards. It is also possible that some information could be provided to the IAEA without being generally declassified; for example, as a result of its inspections in Iraq, the IAEA has access to the nuclear weapons design Iraq developed, which is highly sensitive information.

Assays of weapons components in canisters would reveal the amount of plutonium or HEU in particular components, but as noted in Chapter 4, the committee believes that in most cases this information can be declassified without undue risk to U.S. security interests. If, in particular cases, the amount of plutonium or HEU in particular types of components (or its isotopic composition) were considered particularly sensitive, more complex arrangements could be developed to measure an average content of several differing canisters without providing the content of any specific item.

[17] The IAEA's statute gives the agency the right to "require" that any civilian fissile materials involved in IAEA-supported programs beyond the current needs of member states be deposited in an IAEA-controlled repository, to prevent nationally controlled stockpiling of these weapons-usable materials. Member states, under the statute, would be able to get the material back at any time for any safeguarded peaceful activity. The IAEA has never implemented this "right," however. In 1978, with reprocessing expanding, the IAEA initiated a multination study of "international plutonium storage"

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a separate group to carry out this mission would be a clear sign of lack of confidence in the IAEA. Other nations would inevitably wonder why they should support the IAEA in its global monitoring efforts if the largest nuclear powers did not have confidence in the IAEA for this task. By contrast, granting a significant role to the IAEA in monitoring nondiversion of the material from these sites would signal an endorsement of the agency and an expansion of its role, contributing to the agency's reinvigoration. The committee therefore supports the Clinton administration's September 1993 offer to place U.S. excess fissile materials under IAEA safeguards.

4. *Safeguarded Use or Disposal:* To verify the commitment to non-weapons use, it will be necessary for safeguards and security for these fissile materials to continue after they leave the storage facility for disposition. Safeguarding the processing of pits to other forms without revealing sensitive information would require special precautions, but could be resolved in much the same way described above for the storage site. For example, the canisters could be tagged and sealed, and shipped to the processing facility. Inspectors would examine the facility, check the seals on the canisters, and externally assay them as they entered the facility. They would then assay the canisters that left, to ensure that the plutonium leaving the facility matched the amount that entered, within acceptable limits of error. The facility itself could be reinspected periodically.

   Once the pits were converted to unclassified forms, IAEA safeguards could follow the material throughout its life cycle, as with fissile material in civilian commerce in non-nuclear-weapon states.

5. *IAEA Funding:* The steps outlined above would require increased resources for the IAEA. Resources might be provided specifically for a new assigned task, as has been done to some extent for the IAEA's responsibilities in Iraq. But the agency also needs more resources overall, as described in Chapter 2. The safeguards budget of the IAEA should be substantially increased, and other steps should be taken to strengthen the organization's ability to carry out its old and new roles.

As noted in Chapter 2, however, there are significant political obstacles to gaining agreement to increase the mandatory assessments from the major powers that currently pay for the IAEA safeguards budget. One possible approach is a "voluntary safeguards fund," to which member states desiring improved safeguards could contribute, without requiring a vote or changes in assessments.

(IPS), which resulted in a 1982 report laying out several options, but no agreement was reached to pursue any one. The 1985 NPT Review Conference (the last successful review) called on the IAEA "to establish an internationally agreed effective system of international plutonium storage." On several occasions since 1989, IAEA Director-General Hans Blix has offered the agency's services in safeguarding fissile materials from dismantled weapons. The need to deal with such materials and with the growing excess of civilian separated plutonium has precipitated renewed interest in such concepts in recent years. In late 1992, informal discussions of a possible "international management regime" for fissile materials were held at IAEA headquarters among several of the interested powers, and informal discussions of a safeguarding and transparency regime for fissile materials are continuing.

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Given the scale of the security stakes involved, the United States could easily afford to set a good example by making a substantial contribution to such a fund.

Institutional Arrangements for Physical Security

Both the United States and Russia use substantial forces of armed guards, along with fences, barriers, and other technology, to protect plutonium storage sites from outside attack or insider theft. The United States and Russia are jointly designing the security features of the plutonium storage site to be built in Russia with U.S. assistance, which will be designed to deal with possible external attack by armed bands, as well as other threats such as armor-penetrating bombs dropped from aircraft. The committee believes that it is important for the United States and Russia to agree on high standards of security for such a facility.

Currently, security for plutonium storage is considered a purely national responsibility. Security personnel at the planned storage site in Russia, for example, will be provided entirely by Russia. In principle, however, international personnel could take part not only in safeguarding, but as security forces as well. Conceptually, such an addition might help guard against three threats: (1) an effort by the host nation to take the plutonium back from the store; (2) theft while the host nation retains its authority; or (3) theft accompanied by civil disorder, making the host nation incapable of exercising its authority in that area.

Realistically, foreign guards could provide no more than a tripwire against the first threat, executed by the full power of the host nation. That function might be well enough served by monitors rather than security forces. Against the second threat, national forces should be sufficient, although cooperative programs to improve national responses to this threat should be pursued (see below). However, it would be difficult to protect against the third threat, which might include substantial military or paramilitary forces. The costs and political burdens of permanently stationing an international guard force of sufficient size to cope with such a threat appear excessive. Outside assistance might be brought in at the time such a threat arose, at the request of the state in which the storage site was located. Although this is an extreme scenario, setting up a mechanism for this purpose ahead of time could be useful, as it would greatly simplify orchestrating the response if the need ever arose. For example, the United States, Russia, and possibly other interested parties might agree that in the event of disorder threatening a plutonium storage site in any of their countries, outside forces could be brought in to help protect it, possibly under a United Nations mandate, with the agreement of the state involved.

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Incentives, Ownership, Location, and Management

The concept outlined above would leave the storage sites for excess plutonium physically located in Russia and the United States, under these countries' control, but with international monitoring to verify the commitment to non-weapons use or disposal. The incentive to put material in such stores would derive entirely from the security and political benefits of doing so.

This concept could be modified or supplemented. Financial or other incentives might be provided to encourage placing the maximum amount of material into such stores. Management, control, or outright ownership of the stores and the material in them might be transferred to other parties, such as an appropriate international group. The material might even be relocated to some other country. The concerns motivating such proposals apply primarily to Russian plutonium, but if reciprocity or parallelism is desirable for political reasons, similar steps could be taken with U.S. plutonium.

A Plutonium Purchase

The United States and Russia have agreed in principle to deal with the somewhat parallel case of HEU by a simple purchase. Provided certain conditions are met, the United States will buy 500 tons of HEU, blended down to low-enriched uranium (LEU), and ship it to the United States (see "The HEU Deal," p. 130). If the deal is successfully implemented, financial incentives will be provided to Russia, management and ownership of the material will be transferred, and the material will be physically relocated from Russia to the United States.

A similar deal could be envisioned for excess weapons plutonium. Plutonium, however, is not economically competitive in the current fuels market and, unlike HEU, cannot be blended to a proliferation-resistant form for transport. Hence a plutonium purchase would require a subsidy motivated by security concerns and careful management of the proliferation risks inherent in transport. Either the United States or another country could purchase the plutonium, for eventual storage and disposition in that country, or an international consortium could coordinate the purchase, possibly with the idea of using the plutonium in reactors in Europe and Japan that are already scheduled to use plutonium fuels under existing plans (see Chapter 6).

Since plutonium has no value in the current nuclear fuels market, setting a rational price would be difficult. But given that 500 tons of HEU is to be purchased for $11.9 billion, the price for 50 tons of plutonium (which has the same energy value per ton, but requires much greater investments to use) should not significantly exceed $1 billion and might be substantially less. Like the HEU deal, such a purchase would provide a financial incentive for dismantlement and safeguarded storage, encouraging not only Russia but other states such as Ukraine to follow through on their disarmament commitments. The additional

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incentive from a plutonium deal, however, would be small by comparison to that already planned from the HEU deal, because of the much smaller amount of material.

Such a deal would also remove a substantial quantity of potential weapons material from the former Soviet Union more rapidly than any plausible long-term disposition option could be accomplished, thereby reducing risks of theft or breakout. However, as in the case of the HEU deal, substantial risks would remain after a purchase limited to *excess* weapons plutonium because large numbers of nuclear weapons and large quantities of fissile materials not declared excess would remain in the former Soviet Union.

Such a plutonium purchase would also have important disadvantages. The cost, as noted, could not be justified on economic grounds. Once having acquired the plutonium, the purchasing country or group would have to deal with the tasks of storage and disposition, adding to the problems already being faced with U.S. excess weapons plutonium and civilian plutonium surpluses accumulating elsewhere. This could prompt domestic political difficulties in the country or countries that accepted the large plutonium stock. Transport would create some risks and substantial controversies. There would be political risks for the Yeltsin government, already under fire for selling HEU to the United States, and there would be political risks of a different kind in seeming to give plutonium a commercial value it does not currently merit.

Under certain conditions, the advantages of such a purchase might outweigh the disadvantages. First, a purchase commitment (or any other commitment to provide financial incentives) should not be open-ended and should not provide incentives for the production of additional plutonium. Thus, such an arrangement must either be linked to a monitored cutoff of further production of separated weapons plutonium or be limited by agreement to particular stocks of plutonium already in existence, with the trial between those stocks and the plutonium actually purchased adequately verified. Second, adequate secure and safeguarded storage arrangements would have to be available in the country to which the plutonium was to be shipped. In the case of a U.S. purchase (and probably in other cases as well), gaining political acceptance for such a purchase would probably require not only storage arrangements capable of sustaining general support, but at least the outlines of a plan for long-term disposition of the material.

In short, if Russia expresses interest in a plutonium sale, the United States should not reject the idea out of hand, but should explore the arrangements and conditions under which such a purchase might be carried out. But such purchase schemes should not be the primary focus of U.S. plutonium diplomacy: achieving secure, safeguarded storage is more urgent and more central to the security issues at stake.

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THE HEU DEAL

A conceptually simple approach is being taken to disposition of excess highly enriched uranium from the former Soviet Union: if certain conditions are met, the United States will buy 500 tons of this HEU over the next 20 years, blended down to low-enriched uranium for later resale as reactor fuel. This approach meets several objectives:

1. it removes the material covered by the deal from Russia, thereby reducing risks of theft or breakout;
2. it provides a financial incentive for dismantlement;
3. it provides needed hard currency for the Russian economy;
4. it provides the United States with a needed material at an economical price; and
5. by blending the material down to LEU in Russia and only then shipping it to the United States, it can be accomplished without the risks and controversies of international shipment of potential weapons material.

The deal covers only HEU, not plutonium. A similar plutonium deal would meet the first three objectives, but not the last two.

As of late 1993, the details of the HEU deal were still being negotiated, and the final contract had not yet been signed. In broad outline, the deal would provide for blending down and sale of no less than 10 tons of HEU in each of the first five years, and 30 tons a year thereafter. HEU that is more than 90 percent enriched will be blended down to 4.4 percent enriched LEU, which the United States will purchase at an initial price of $780 per kilogram—somewhat above the spot market price, but below the price the U.S. Enrichment Corporation charges its commercial customers. At that price, the value of the deal would amount to some $12 billion, but the agreement specifies that the price will change with market conditions.[1] The Russian government plans to do the blending in Russia, though there is an option to do some of the blending work in the United States if Russian facilities cannot keep up the agreed pace.

The United States has indicated that it will not begin implementing the HEU deal until Russia and the other states of the former Soviet Union where nuclear weapons are located have agreed among themselves on an equitable sharing of the proceeds. Russia and Ukraine have agreed in principle that Ukraine deserves compensation for the HEU (but not the plutonium) in the strategic warheads still located on its territory, but they disagree over whether Ukraine should receive compensation for the materials in the tactical warheads removed from its territory during 1991 and 1992. The Russian Minister of Atomic Energy, Victor N. Mikhailov, has criticized

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the U.S. insistence on such sharing as an unjustified intrusion into Russia's relations with its neighbors. Mikhailov has also demanded revision of a 1992 trade agreement limiting commercial access to the U.S. uranium market by the states of the former Soviet Union—which these states accepted to avoid punitive tariffs for alleged "dumping" of uranium products at below production cost.

Russia and the United States are negotiating the details of "transparency" measures that will allow the United States to confirm that the LEU it is purchasing did in fact come from HEU (and will allow Russia to confirm that the material is used only for peaceful purposes). The United States, however, will not have any means of ensuring that the HEU came from weapons rather than other HEU stocks, except for Russian assurances and unilateral U.S. intelligence capabilities.

The HEU deal meets its security objectives only in part. Because the amount of HEU to be blended and shipped in the first few years is small, the deal will do relatively little to reduce the risks of theft of nuclear materials during the current upheavals, when those risks may be most urgent. Even when the deal is complete, two decades hence, large stocks of HEU will remain. Moreover, although the Russian government had previously informed the United States that the 500 tons of HEU envisioned in this deal represented all the HEU it expected to be surplus to its military requirements, Mikhailov has recently indicated that the total Russian stockpile includes some 1,250 tons of HEU, which, if true, would make the 500 tons to be purchased only a fraction of the total. In addition, the lack of monitoring to ensure that the material purchased comes from weapons rather than other stocks weakens the deal's effect as a financial incentive for dismantlement. But if Russia and other former Soviet states can agree on sharing the proceeds, the HEU deal will provide a significant financial incentive for Ukraine, Kazakhstan, and Belarus to fulfill their denuclearization commitments. In financial terms, the HEU deal is by far the largest-scale joint effort in denuclearization between the United States and Russia, making its success central to the future of cooperation in these areas. Indeed, the $12 billion dollar value of this deal may exceed the total cost of dismantlement. storage, and disposition of excess nuclear weapons and fissile materials in the former Soviet Union.

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[1] Rather than being blended with natural uranium, or with the depleted uranium waste from enrichment plants, the two sides have agreed that the HEU will be blended with 1.5 percent enriched uranium. This will substantially increase the amount of material that must be mixed with the HEU to reduce it to the agreed enrichment, but will reduce the final concentration of uranium-234 (U-234), an undesirable isotope that tends to be separated with U-235 during enrichment.

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Alternatives to Outright Purchase

Outright purchase is not the only means to provide incentives or shift management. The essence of a purchase can be divided into three separate issues: incentives (financial or otherwise); transfer of ownership, control, or management; and transfer of location.[18]

Financial Incentives. The United States is already providing some financial incentive for secure storage of Russian fissile materials by helping to finance a new fissile material storage site. Additional financial incentives might be based on payment of specified sums for placement of specified quantities of plutonium into safeguarded storage. Provided that they not become open-ended commitments, the committee believes such incentives would be desirable and should continue to be explored.

Transferring Ownership or Control. Rather than being solely owned and controlled by the nation from whose weapons it came, the storage site for excess plutonium, and the plutonium within it, might be owned, controlled, or managed by another group, either a new international consortium or an existing international organization such as the IAEA. A wide range of possibilities exists, from shifting only a few limited management and accounting responsibilities to the international group, to complete transfer of ownership, along with decision-making authority over the ultimate disposition of the plutonium. Some of the points along this spectrum have been examined in IAEA discussions of "international plutonium storage," or of an "international management regime" for fissile materials.[19] Like purchase agreements, schemes for transferring control over plutonium might encounter opposition in Russia from those who continue to see plutonium as a national patrimony. Such concerns might be reduced if U.S. plutonium were treated in a parallel way.

Transferring Location. In most cases, a transfer of location would also imply a transfer of ownership, as in the purchase concepts outlined above. One could also imagine, however, that Russian plutonium might be shipped elsewhere for storage, while remaining under Russian ownership, with Russia being able to request its transfer back at a later time. Given the many political

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[18] As an example of how these factors might be divided, one group of American experts has suggested forming an international consortium that would provide financial incentives (amounting to some $20,000 per kilogram) to Russia and the United States for placing plutonium into secure, safeguarded storage sites, which would be managed and guarded by the consortium but located in Russia and the United States. (The U.S. financial contribution to the consortium might just balance the payments the United States would receive, so that the cost of funding the Russian store would largely be borne by Europe and Japan.) See Allison et al., op. cit., pp. 125-128.

[19] See van Doren, op. cit. In discussions in the late 1970s and early 1980s, basic issues of sovereignty over the material in the international plutonium storage arrangement—particularly whether the state that deposited the plutonium could withdraw it at will for peaceful purposes, or whether the storage organization would have authority to approve or disapprove withdrawals—were among the principal stumbling blocks to agreement.

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complications and the security issues of two-way transport, this approach does not appear promising.

REDUCING THE RISK OF NUCLEAR THEFT IN THE FORMER SOVIET UNION

As described in Chapter 2, the risks of theft of fissile materials—or even assembled weapons—in the former Soviet Union are serious. Action to improve security and accounting is urgent, as many of the Russian officials responsible have acknowledged. Every day that goes by poses additional risks that fissile materials may be stolen and wind up in the hands of potential proliferators.

Both the HEU deal and the planned construction of a fissile material storage site in Russia address this issue in part, but both deal only with fissile materials from weapons dismantlement that Russia considers excess. Yet in addition to these quantities there are substantial stocks of fissile materials not incorporated in weapons throughout the Russian nuclear weapons complex; substantial stocks of civilian separated plutonium at the Mayak reprocessing plant; and a wide variety of military and civilian research facilities with more than enough fissile materials for a bomb. Nuclear materials in Ukraine, Kazakhstan, and other former Soviet states must also be adequately secured and accounted for.

The United States is working with several of the states of the former Soviet Union to provide assistance in improving security and accounting for these nuclear materials, but only very limited steps have been taken so far, and the scale of the effort is small by comparison to the scale of the problem. As part of the Nunn-Lugar Safety, Security, and Dismantlement (SSD) effort, the United States is planning to provide Russia $10 million for these purposes (in addition to the planned assistance for the secure storage facility), along with $7.5 million for Ukraine, and $5 million for Kazakhstan. In Russia, the effort will include assistance in improving Russia's "state system" of material accounting and control, training courses similar to those regularly provided to international groups at the U.S. national laboratories, and the construction of "model" safeguards and security systems at two civilian sites—both of which process only non-weapons-usable LEU—over a period of roughly two years. As of the fall of 1993, none of these funds had been expended, as the relevant implementing agreement had just been signed.[20] The IAEA and other countries also plan to provide limited assistance in material control and accounting, but none on a scale comparable even to the U.S. effort.

These efforts have been considerably hampered by the ongoing turmoil in the former Soviet Union, disputes among agencies there, the continuing legacy of secrecy and mistrust, lack of priority and political impetus, and limited

[20] See U.S. Department of Defense, op. cit. The implementing agreement for material control and accounting was signed on September 2, 1993.

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funds. Although an initial agreement on accounting assistance was drawn up in the spring of 1993, for example, it took nearly half a year of review by Russia before it was finally signed in September 1993. Through late 1993, Russian officials had refused outside assistance that would involve foreign intrusion at military sites, and the United States had not pressed the point at a high level or offered comparable access to U.S. sites. As a result, direct U.S. assistance in accounting and security will cover only the two model civilian sites. Neither the major military sites, where the bulk of the fissile materials are stored, nor the many civilian sites with weapons-usable materials would be directly affected. The United States hopes that Russia will apply the lessons learned from joint work on the model sites to improve procedures elsewhere.

The committee recommends a more urgent and comprehensive approach at a significantly higher level of funding, with an emphasis on cooperation in addressing the most immediate risks. Western countries, including the United States, should press Russia and the other states of the former Soviet Union to take a number of steps urgently—within weeks or months, rather than years—and they should be willing to provide necessary equipment and funds for these purposes.

In particular, Western countries should press for and offer assistance for the following:

- Immediate installation of appropriate portal-monitoring systems to detect any theft of fissile materials, as well as adequate armed guard forces, at *all* sites where enough weapons-usable fissile material to make a nuclear weapon is stored.
- An urgent program of security and accounting inspections and improvements at all of these sites. As recently as the mid-1980s, the United States undertook such a crash program at its own nuclear weapons complex, and made critical improvements, such as the installation of portal monitors, within days of the initial inspection in some cases.[21]
- Improved economic conditions for personnel responsible for accounting and security for weapons and fissile materials, to reduce incentives for corruption and insider theft.
- Improved national oversight of security and safeguards, with a strengthened basis in law. In Russia, this would involve strengthening the role of GOSATOMNADZOR, while in other former Soviet states it would involve strengthening or creating comparable organizations.
- Consolidation of fissile material storage and handling where possible.
- Conversion of research reactors to run on low-enriched uranium fuels, reducing the number of sites where weapons-grade fissile materials are used.

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[21]*Adequacy of Safeguards and Security at the Department of EnergyNuclear Weapons Production Facilities*, hearing before the House Energy and Commerce Subcommittee on Oversight and Investigations, March 6, 1986.

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- Greater Western participation and cooperation in safeguards and security, ideally at all fissile material sites, but at all civilian sites at a minimum. This might begin with exchanges of information concerning security procedures at each of the sites where significant quantities of fissile materials are stored and handled, ideally supplemented by visits to each of these sites, to provide the basis for more educated offers of assistance in making improvements. These initial exchanges should be followed by establishing in-depth working-level cooperation on means to improve security and safeguards.
- Regularized, as well as emergency, working-level cooperation in monitoring reports of alleged diversions. Currently, consultations on such reports are generally carried out at a high and rather formal level, with much helpful detail omitted. The states of the former Soviet Union are likely to have the best information on thieves and dealers within their borders, whereas outside states may have better information on the network of buyers. Working together would help the relevant intelligence agencies respond to these myriad reports.

To help overcome current Russian resistance to Western participation in improving safeguards and security at military sites, the United States should be quite open about the problems it has uncovered in the past in its own weapons complex, and should be prepared to offer information about and access to U.S. sites. Such an offer might be desirable even if it were not required for political reciprocity, in order to demonstrate the security procedures used in the U.S. system.

Joint U.S.-Russian development of improved technologies for accounting and security for nuclear materials would also be valuable, providing practical tools to reduce serious risks, while at the same time making productive use of the talents of former weapons scientists and engineers on both sides.

Ultimately, it would be desirable if the high standard for security and material accounting that should be set for the planned jointly built storage facility were applied to *all* fissile materials in Russia. One means to achieve this would be for Russia to follow the same approach that DOE plans for the United States, consolidating all of its stored plutonium and HEU at a single site. As at the U.S. site, IAEA safeguards such as those advocated in this chapter might be applied at that storage site, possibly with the portion of the material still reserved for weapons use held in a separate area not subject to inspection, or subject to less intrusive measures. Such a dual approach would require significantly expanding the size of the storage facility currently planned or making explicit provision for possible subsequent construction of additional modules. The advantages of such an approach are sufficiently compelling that the committee believes the United States should begin to discuss it with Russia. It should be remembered, however, that even after such consolidation, a number of facilities would remain at which working stocks of fissile materials would have to be accounted for and secured.

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Alternatively, if the material cannot be brought to the storage facility, some of the cooperative approaches to be developed for the storage facility might be brought to the material. It might be desirable, for example, to have joint perimeter monitoring at existing fissile material sites to guard against theft.[22] This would complement the perimeter monitoring that each side already has in place (or should be urged to put in place) at its own sites. For example, a small cadre of individuals from the United States could take up residence at each of the major Russian sites, taking part in portal inspections to ensure that fissile material was not being removed without authorization. This would go a long way toward resolving doubts and uncertainties concerning the myriad reports of diversion now appearing, since any effort to bribe or overwhelm the portal guards would then have to include foreign personnel at the site as well.

Although the main problem in this area, at present, is likely to be in Russia, such a program would certainly require offering comparable access to U.S. sites. Since perimeter-monitoring systems under each side's own control already exist, such joint cooperation might be set up quickly once a decision was made, with a minimum of added intrusion on activities at the sites. In particular, the perimeter monitors would not necessarily need to be informed about any of the activities going on within the site; they would only oversee the guards who check materials that leave the facility.

The committee believes that measures such as these could potentially provide large security benefits for modest costs and should be addressed immediately.

OTHER PLUTONIUM AND HEU WORLDWIDE

A number of countries are pursuing nuclear fuel cycles that involve the use, processing, and transport of separated plutonium. In addition, HEU is widely used in research reactors. These materials are usable for nuclear weapons, and therefore their use requires careful attention to safeguards and security to mitigate the proliferation risks. As noted in Chapter 2, standards of safeguards and security for these materials vary widely and are less stringent than those applied to similar materials in military use. This situation needs to be changed.

To mitigate these proliferation risks and manage the politics surrounding the use of these materials, some have advocated a regime internationalizing the storage (and possibly use) of these materials, in a concept the IAEA is now calling an "international management regime." Safeguarded storage for excess fissile materials from dismantled weapons in the United States and Russia can and should be seen as a first step toward building such a broader regime. Negotiations should be pursued to:

[22] For a similar proposal, see Jonathan Dean, "Safeguarding Nuclear Warheads and Fissile Materials in Ukraine and Russia," Union of Concerned Scientists, September 22, 1993.

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1. create a global cutoff of all unsafeguarded production of fissile materials;
2. use the U.S.-Russian safeguarded storage regime recommended above as a base for a broad international storage and management regime for fissile materials, including registration and safeguards for all civilian separated plutonium and HEU;
3. extend the U.S.-Russian declaratory regime mentioned above to a global regime of public declarations of stocks of fissile materials;
4. agree on higher standards of physical security for these materials, with an international organization given authority to inspect sites to monitor whether the standards are met; and
5. agree on cooperative international approaches to manage the reprocessing and use of plutonium to avoid building up excess stocks.

The proliferation risks from civilian plutonium and HEU programs justify greater efforts and expenses to mitigate them than are applied today. In particular, safeguards and security for civilian separated plutonium and HEU should be increased to a level comparable to those applied to plutonium in military stocks. States using nuclear power should also reexamine the adequacy of their measures to ensure against diversion of spent fuel. Spent fuel that is decades old is of greater concern than fresh spent fuel, and should meet special standards; ultimately, very old spent fuel will have to be subject to security comparable to that used for unirradiated plutonium-bearing materials. Applicable international standards on these points should be revised to reflect these perspectives.

RECOMMENDATIONS

- The United States and Russia should place plutonium excess to military needs in safeguarded storage as soon as practical.
- Stored excess fissile materials committed to non-weapons use or disposal by the United States and Russia should be placed under international safeguards (possibly combined with bilateral monitoring). In the interest of speed, monitoring of storage could initially be a bilateral U.S.-Russian effort, but the IAEA should be brought into the process rapidly.
- The United States should continue providing assistance for a Russian fissile material storage facility, which should be designed to consolidate all excess weapons materials at a single site, to facilitate security and international monitoring.
- Plutonium from dismantled weapons should continue to be stored as intact pits for now. Deformation of these pits and perhaps other steps to reduce the rearmament risk should be given serious consideration, and should be undertaken if they can be accomplished at relatively low cost and ES&H risk.

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- Pits should be stored in sealed containers, with monitors permitted to assay the containers externally without observing the pits' dimensions, to provide adequate safeguards without compromising sensitive weapons design information.
- Once definite disposition options have been chosen, the plutonium should be converted expeditiously to whatever form is required as part of the disposition process.
- Financial or other incentives might be provided to encourage Russia to place the maximum amount of material into monitored storage. With the condition that these not be an open-ended commitment or provide any incentive for continued production of separated plutonium, such incentives would be desirable and should continue to be explored.
- The safeguards budget of the IAEA should be substantially increased, and other steps should be taken to strengthen that organization's ability to carry out its critical responsibilities. One promising approach would be the creation of a voluntary fund, to which nations interested in improved safeguards would make contributions above and beyond their fixed allocation.
- Appropriate arrangements for intermediate storage are to a large extent decoupled from long-term disposition decisions and should be considered more urgent.
- Urgent steps are needed to improve safeguards and security for all fissile materials in the former Soviet Union, including materials beyond those considered excess. The committee recommends a comprehensive approach at a significantly higher level of funding, with an emphasis on cooperation in addressing the most immediate risks. Western countries, including the United States, should press Russia and the other states of the former Soviet Union to take a number of steps urgently, and should be willing to provide necessary equipment and funds for these purposes. In particular, Western countries should press for and offer assistance for:

1. immediate installation of appropriate portal-monitoring systems to detect any theft of fissile materials, as well as adequate armed guard forces, at *all* sites where enough weapons-usable fissile material to make a nuclear weapon is stored;
2. an urgent program of security and accounting inspections and improvements at all of these sites;
3. improved economic conditions for personnel responsible for accounting and security for weapons and fissile materials, to reduce incentives for corruption and insider theft;
4. improved national oversight of security and safeguards, with a strengthened basis in law. In Russia, this would involve strengthening the role of

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GOSATOMNADZOR, while in other former Soviet states it would involve strengthening or creating comparable organizations;

5. consolidation of fissile material storage and handling where possible;
6. conversion of research reactors to run on low-enriched uranium fuels, reducing the number of sites where weapons-grade fissile materials are used;
7. greater Western participation and cooperation in safeguards and security, ideally at all fissile material sites, but at all civilian sites at a minimum; and
8. regularized, as well as emergency, working-level cooperation in monitoring reports of alleged diversions.

- The steps outlined by the committee to improve safeguards and physical security for fissile materials in the United States and Russia should set a standard for a regime for improved management of such materials in civilian use throughout the world. Negotiations should be pursued to:

1. create a global cutoff of all unsafeguarded production of fissile materials;
2. use the U.S.-Russian safeguarded storage regime recommended above as a base for a broad international storage and management regime for fissile materials, including registration and safeguards for all civilian separated plutonium and HEU;
3. extend the U.S.-Russian declaratory regime mentioned above to a global regime of public declarations of stocks of fissile materials;
4. agree on higher standards of physical security for these materials, with an international organization given authority to inspect sites to monitor whether the standards are met; and
5. agree on cooperative international approaches to manage reprocessing and use of plutonium to avoid building up excess stocks.

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6

Long-Term Disposition

INTRODUCTION

Long-term disposition of the excess plutonium from dismantled nuclear weapons—the third stage in the process beginning with dismantlement of weapons and intermediate storage of fissile materials—will be a long, complex, and expensive endeavor.

- All of the plausible options stretch out over decades, counting both the time required to get ready to begin and the time needed to complete the disposition campaign.
- All options are likely to involve a net economic cost, rather than providing a net profit from this material.
- All options involve unresolved issues and risks of uncertain magnitude.
- None of the options is sufficiently developed to be chosen as the preferred approach until outstanding questions are answered.

This chapter offers not a final answer but a road map for arriving at one; it is intended to provide guidelines for the necessary national and international debate to come, to narrow the focus of attention to the subset of options most likely to minimize risks, and to provide plausible end points for the dismantlement and storage activities now under way.

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In considering this situation, the committee has reached the following set of recommendations:

- Because of the long times required for all disposition options, fissile material storage arrangements lasting well over a decade will be an essential part of any disposition policy (see Chapter 5). These storage arrangements should be designed to meet the same stringent standards of security and accountability applied to stored weapons, and they should include international monitoring. Because of the uncertainties surrounding all disposition options, these intermediate storage approaches must be designed to be capable of extension for many decades if necessary. The appropriate arrangements for intermediate storage are to a large extent decoupled from long-term disposition decisions and are currently more urgent.
- Storage should not be extended indefinitely. Because of the liabilities of indefinite storage of excess weapons material for the nonproliferation and arms reduction regimes, the risk of breakout involved in such storage, and the risks of theft in the event of a breakdown in government authority, there are substantial reasons to pursue other disposition approaches that provide additional barriers against use of this material in weapons. Indeed, one of the key criteria by which disposition options should be judged is the speed with which they can be accomplished, and thus the degree to which they curtail the risks of prolonged storage.
- Disposition options other than extended storage should be pursued only if they reduce overall security risks compared to leaving the material in storage, when both the final form of the material and the risks of the various processes needed to get to that state are considered. In the current unsettled circumstances in Russia, this minimum criterion is not trivial.
- To the extent practicable, safeguards and security measures should maintain the "stored weapons standard" of accounting and security throughout the disposition process. The process must take place under agreed monitoring and security that form part of the overall regime for management of fissile materials described in previous chapters.
- An appropriate standard for the final product of disposition options is that they transform the weapons plutonium into a physical form that is at least as inaccessible for weapons use as the much larger and growing stock of plutonium that exists in spent fuel from commercial nuclear reactors. (This existing problem will itself change over time as the radioactivity decays, repositories or monitored retrievable storage sites become available, and approaches to safeguards and security and nuclear fuel cycles evolve.) Incurring substantial additional costs, complexities, risks, or delays in order to go further and eliminate the excess weapons plutonium completely or nearly so would not be justified

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unless the same approach were to be taken with the global stock of civilian plutonium.

- The two most promising alternatives for the purpose of meeting the spent fuel standard are:

1. The *spent fuel option*,[1] which has several variants. The principal one is to use the plutonium as once-through fuel in existing civilian nuclear power reactors or their evolutionary variants. Candidates for this role are U.S. light-water reactors (LWRs), Russian LWRs, and Canadian deuterium-uranium (CANDU) reactors. The use of European and Japanese reactors already licensed for civilian plutonium should also be considered for Russian weapons plutonium.
2. The *vitrification option*, which would entail combining the plutonium with radioactive high-level wastes as these are melted into large glass logs. The plutonium would then be roughly as difficult to recover for weapons use as plutonium in spent fuel.

A third option, *burial in deep boreholes*, has until now been less thoroughly studied than options 1 and 2, but could turn out to be comparably attractive.

Further research is needed to answer important outstanding questions concerning each of these three options.

- For the spent fuel option, existing or partly completed reactors are preferred over newly built reactors, to avoid the delay and capital cost of building entirely new facilities. If problems of licensing and public approval for existing reactors prove insurmountable, one or more new reactors might be built on a government-owned site; if so, these should be reactors of sufficiently well-proven design so as not to create additional technical and licensing uncertainties. Reactors of more advanced design examined by the committee do not offer sufficient advantages for this mission to offset the delays and extra costs their use would entail.
- Although the spent fuel standard applied to excess plutonium is an appropriate goal for next steps, further steps should be taken to reduce the proliferation risks associated with nuclear power and the global stock of plutonium, including plutonium in spent fuel. Options for near-total elimination of plutonium may have a role to play in the longer-term effort to reduce the risks posed by global plutonium stocks. Research on defining and exploring these options should be continued at the conceptual level.

[1] The spent fuel *option*, in which the weapons plutonium would actually be converted to spent fuel, should not be confused with the spent fuel *standard*: it is merely one means of meeting that standard. As discussed later, spent plutonium fuels would have some differences from ordinary spent fuels, including higher plutonium concentrations.

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- Institutional issues in managing plutonium disposition may be more complex and difficult to resolve than the technical ones. The process must be carefully managed to provide adequate safeguards, security, transparency, and protection for environment, safety, and health; to obtain public and institutional approval, including licenses; and to allow adequate participation in the decision making by all affected parties, including the U.S. and Russian publics and the international community. Adequate information must be made available to give substance to the public's participation. A more effective decision making process to address these issues is needed within both the U.S. and the Russian governments, as discussed in Chapter 1.
- It is important to begin now to build consensus on a road map for decisions concerning long-term disposition of excess weapons plutonium. Because disposition options will take decades to carry out, it is critical to develop options that can muster a sustainable consensus.

The remainder of this chapter outlines the considerations that led to these conclusions. It begins by describing the categories into which the many technical options for long-term disposition can be divided and the criteria for judging among them. It then goes on to discuss each option and how it fares under those criteria. Finally, it outlines the committee's recommendations.

THE RANGE OF CHOICE

The options for long-term disposition can be divided into three broad classes, as illustrated in Figure 6-1:

1. *Indefinite Storage:* In this approach, the plutonium would continue to be stored in directly weapons-usable form indefinitely, with no specific decision concerning whether, when, and how storage would be terminated.[2] During such storage, safeguards and security would provide the primary barrier to proliferation. Political measures, such as a formal commitment to non-weapons use and continuing safeguards, would provide the primary barrier to reuse of the material for weapons by the state from whose weapons the material came. Although intermediate storage is essential to all disposition options, for reasons already mentioned the committee does not recommend that it be extended indefinitely.
2. *Minimized Accessibility:* In this concept, barriers would be created—physical, chemical, or radiological—to make the steps needed to use the plutonium in weapons (acquisition of the plutonium, processing, weapon manufacture) more difficult either for potential proliferators or for the state from whose

[2] In separating "indefinite" storage from "intermediate" storage, this report uses "indefinite" to mean approaches in which storage itself is considered the disposition option, and no end point to the storage has been defined. In this nomenclature, storage would be considered "intermediate" even if it lasted for several decades, if the material were awaiting processing in a chosen disposition option.

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weapons it came. The plutonium would continue to exist, and some form of safeguards would continue to be required. The spent fuel, vitrification, and deep-borehole approaches are examples.

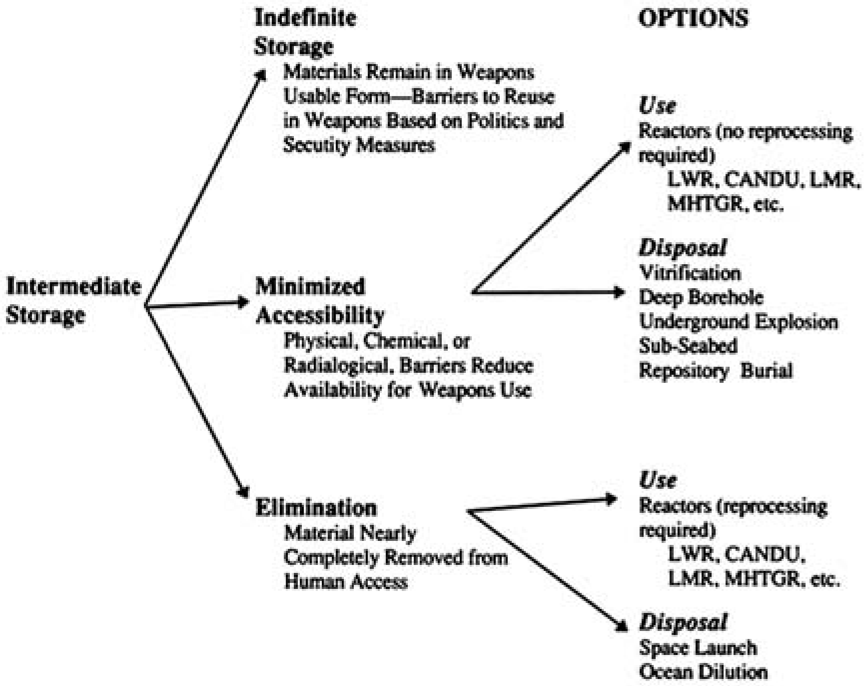

FIGURE 6-1 Plutonium disposition

3. *Elimination:* In this concept, the plutonium would be removed from human access completely, or nearly so, for example, by fissioning the plutonium atoms or by launching it into deep space. The point in such a process at which the plutonium can be considered "eliminated"—for example, whether burning 99 percent of the plutonium would be sufficient—is somewhat arbitrary, but any "elimination" option should ensure that retrieving enough plutonium for a nuclear explosive from whatever remains would be extremely difficult. One plausible standard is to describe any option in which only a few grams of plutonium would remain in a large truckload of waste as an elimination option.[3]

[3] The International Atomic Energy Agency (IAEA), for example, considers that materials no longer require safeguards if the remaining fissile material in them has been "consumed," or so diluted as to be "practically irrecoverable" for weapons use. Quantitative measures for termination of safeguards, which might provide one standard for judging when to consider fissile material "eliminated," have not yet been finalized. Interview with Thomas Shea, IAEA Safeguards Division, August 1993. See, for example, A. Fattah and N. Khlebnikov, "A Proposal for Technical Criteria for Termination of

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Use or Disposal. A complementary categorization is whether the plutonium would be *used or disposed of.* The use options would fission some fraction of the plutonium in power reactors, converting its energy content into electricity. The disposal options would throw away the plutonium's energy content. Since plutonium is more expensive to use as nuclear fuel than widely available low-enriched uranium, either the use or the disposal options would require a subsidy. The different signals relating to civilian nuclear power that would be sent by using excess plutonium or throwing it away are discussed in more detail below.

U.S. and Russian Contexts. It is possible—even likely—that the optimal approaches to long-term plutonium disposition will be different in the United States and Russia. The risks involved in storing, handling, processing, and transporting plutonium are much higher in Russia under present circumstances, and the two countries' economies and plutonium fuel policies are different. Most of the key officials responsible for these issues in the Russian government strongly prefer options that use surplus weapons plutonium to generate electricity in reactors; it would be difficult to convince Russia to pursue disposal options in the near term (though perhaps not impossible, particularly with sufficient financial incentives).

Although U.S. and Russian disposition approaches may differ, rough parallelism in the timing and scale of long-term disposition would be desirable, so that both nations' available plutonium stocks would remain comparable. After long-term disposition, neither nation's excess plutonium should be much more accessible for use in weapons than the other's.

While the United States and other industrialized countries cannot dictate particular disposition options to Russia, they will have a significant influence on Russian decisions in a variety of ways—ranging from simply setting an example on the one hand, to financial assistance, negotiated agreements to pursue particular approaches, or outright purchase of former Soviet weapons plutonium on the other.

Other Forms of Military Plutonium. The primary focus of this report is the excess weapons plutonium resulting from arms reductions, which is initially in the form of pits from dismantled nuclear weapons. Both the United States and Russia, however, also have large quantities of military plutonium in scrap and residues from past operations of their nuclear weapons complexes, most of which are also likely to be considered excess. Although the amount of plutonium in these forms is smaller than the amount in pits that will result from arms reductions, the volume is much greater; the variety of forms of material is wide; and the environment, safety, and health (ES&H) risks are substantial for

Safeguards for Materials Characterized as Measured Discards," *Journal of Nuclear Materials Management*, May 1991.

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some forms. Even characterizing the constituents of these materials accurately is difficult.

Some of these materials can readily be processed to plutonium metal or oxide that could then be fed into many of the disposition options described below. Some reactor options (typically the more advanced ones that would take longer to bring on-line) are more capable than others of handling variations in the form of the initial fuel feed, though there are materials that none of the reactor options could plausibly handle. Moreover, processing of some of these materials would raise difficult environmental issues of its own. The vitrification option, described below, may be a particularly promising approach for stabilizing and ultimately disposing of the plutonium in these less tractable forms.

CRITERIA FOR DISPOSITION OPTIONS

Security issues should be the primary criteria for choice among the long-term disposition options. Each long-term disposition approach generates risks and opportunities with respect to theft, rearmament, and the arms reduction and nonproliferation regimes that depend on political and technical factors that will evolve over the long time periods involved in disposition. The committee judges the following security risks related to long-term disposition choices to be of greatest concern:

Risks of Storage: Prolonged storage of excess weapons plutonium would mean a continuing risk of breakout, as well as of theft from the storage site. In addition, extended storage of large quantities of excess fissile materials, particularly in the form of weapons components, could undermine the arms reduction and nonproliferation regimes. Thus, long-term disposition options should minimize the time during which plutonium is stored in accessible forms. The timing for each long-term disposition option is dependent on three factors: its technical readiness or uncertainty, the speed with which public and institutional approval could be gained, and the time required to implement it once developed and approved.

Risks of Handling: Nearly all disposition options other than indefinite storage require processing and usually transportation of plutonium, in ways that could increase access to the material and complicate accounting for it, thus increasing the potential for diversion and theft. In order to ensure that the overall process reduces net security risks, an agreed and stringent standard of security and accounting must be maintained throughout the disposition process, approximating as closely as practicable the security and accounting applied to intact nuclear weapons. The committee calls this the "stored weapons standard." Hence, choices among long-term disposition options should be weighted in favor of those that minimize:

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- the number of transport steps, and the risks involved in each;
- the number of sites at which plutonium is handled, and the risks at each of those sites; and
- any processing steps with high accessibility and low accountability.

Risks of Recovery: A third key security criterion for judging disposition options is the risk of recovery of the plutonium after disposition. The committee believes that options for the long-term disposition of weapons plutonium should seek to meet a "spent fuel standard"—that is, to make this plutonium roughly as inaccessible for weapons use as the much larger and growing quantity of plutonium that exists in spent fuel from commercial reactors. Options that left the plutonium more accessible than this existing stock would mean that this material would continue to pose a unique safeguards problem indefinitely. Conversely, as long as civilian plutonium exists and continues to accumulate, options that went further than the spent fuel standard and sought to eliminate the excess weapons plutonium entirely would provide little additional security, *unless the same were done withthe much larger amount of civilian plutonium*. Thus, options for the next steps in *long-term disposition of weapons plutonium should focuson those in the "minimized accessibility" class.*

Over the longer term, however, steps should be taken to go beyond the current spent fuel standard, to further reduce the accessibility for use in weapons of the entire global stock of plutonium. Elimination options are among the possibilities for this purpose and could be seen as a second, long-term step for all plutonium (both military and civilian).

The difficulty of using plutonium in spent fuel for nuclear explosives arises from its chemical dilution in the fuel (with plutonium typically consisting of roughly 1 percent of the spent fuel weight); the radioactivity of the fission products with which the plutonium is mixed (which, for years after the fuel leaves the reactor, would give anyone attempting to the handle the spent fuel without appropriate protection a lethal dose of radiation within minutes); and the isotopic composition of the plutonium (which includes more of the less desirable isotopes of plutonium than weapons-grade material does, somewhat complicating the construction of nuclear explosives). (See "How Accessible is Plutonium in Spent Fuel?" p. 150.) Eventually, physical barriers will be imposed as well, when this material is consigned to geologic repositories; these physical barriers will have to compensate for the long-term decline of the radiological barrier.

Chemical barriers alone, such as diluting the plutonium or combining it chemically with other elements, will not be sufficient to match this combination of chemical, radiological, and isotopic barriers, and therefore cannot meet the spent fuel standard. Thus, the leading options the committee has examined involve both chemical and radiological barriers (in the case of the spent fuel and vitrification options) or substantial physical barriers (in the case of the deep-borehole option).

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The three security criteria just outlined represent a kind of coarse filter for disposition options: any option that cannot bring the weapons plutonium to the spent fuel standard within a few decades with low to moderate security risks along the way does not deserve further consideration.

Signals Relating to Civilian Nuclear Fuel Cycles. The goal of long-term disposition should be not only to ensure that the plutonium from dismantled weapons is not reused in weapons, but also to reduce *net* security risks from all fissile materials. Thus, policymakers must be attentive to possible indirect effects that the choice of disposition options might have on the proliferation risks posed by other fissile materials in the world, as well as its direct effects on the surplus weapons material. The political signals sent by the choice of particular disposition approaches might encourage the development and use of more proliferation-resistant nuclear fuel cycles; encourage the use of more proliferation-prone nuclear fuel cycles; or serve to set a standard for improved safeguards and security for other fissile materials.

Under the Carter administration, the United States decided not to reprocess civilian plutonium or pursue plutonium fuel cycles, and launched a major international effort to convince other countries that such separated plutonium fuel cycles were uneconomical and posed significant proliferation risks. Elements of that policy were incorporated in the Nuclear Non-Proliferation Act of 1978, which remains U.S. law. Although the Reagan and Bush administrations reversed the Carter administration's opposition to domestic use of separated plutonium, for economic reasons none has ensued. Both of these administrations continued to strongly oppose plutonium separation in countries judged to pose proliferation risks, while raising no objections to continuing plutonium separation programs in Japan and Europe. On September 27, 1993, the Clinton administration announced a nonproliferation initiative that makes clear that, while the United States will not interfere with reprocessing in Japan and Europe, "the United States does not encourage the civil use of plutonium and, accordingly, does not itself engage in plutonium reprocessing for either nuclear power or nuclear explosive purposes." The initiative called for an exploration of "means to limit the stockpiling of plutonium from civil nuclear programs."[4]

Given this background, policymakers will have to take into account the fact that choosing to use weapons plutonium in reactors would be perceived by some as representing generalized U.S. approval of separated plutonium fuel cycles, thereby compromising the ability of the U.S. government to oppose such fuel cycles elsewhere. Conversely, choosing to dispose of weapons plutonium without extracting any energy from it could be interpreted as reflecting a generalized U.S. government opposition to plutonium recycle. Either choice could have an impact on fuel cycle debates now under way in Japan, Europe, and Russia.

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[4] White House Fact Sheet, "Nonproliferation and Export Control Policy," September 27, 1993.

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HOW ACCESSIBLE IS PLUTONIUM IN SPENT FUEL?

The goal of making weapons plutonium as inaccessible for weapons use as plutonium in commercial spent fuel raises the obvious question: How accessible is the plutonium in spent fuel?

The answer depends on how one answers a prior question: Accessible to whom? There are three main classes of possibilities: (i) countries with established reprocessing capabilities; (ii) countries without such capabilities, but with spent fuel in their possession; and (iii) countries or subnational groups without significant nuclear programs, who would have to acquire spent fuel before they could begin recovering the plutonium.

Four primary factors affect the usefulness of civilian spent fuel as a potential weapon material: (1) the intense radioactivity of the fission products in the fuel (which decays with time); (2) the need for chemical separation of the plutonium from the fuel (which must be done by remotely operated equipment as long as the fuel remains intensely radioactive); (3) the isotopic composition of the plutonium (reactor-grade plutonium being a less desirable weapons material than weapons-grade plutonium); and (4) if the party in question does not own the spent fuel, the difficulty of acquiring it.

For countries with established military or commercial reprocessing capabilities, the need to separate plutonium from spent fuel would pose effectively no barrier at all to recovering enough material for one or a few nuclear weapons, and recovering more would be only a matter of time and cost. Countries with such sophisticated nuclear technology, however, might choose to produce weapons-grade plutonium instead, as has every nation that has produced plutonium-based nuclear explosives to date.

For countries with no established reprocessing capability, recovering plutonium from spent fuel would be more difficult. All the essential processes are authoritatively described in the open literature, however, and the requisite technologies are available on the open market. Indeed, rather than building the large and expensive facilities needed to separate plutonium on a commercial scale, a potential proliferator could rely on simple and relatively low-cost facilities, designed to separate enough plutonium for a few weapons, with little attention to safety and health. Such a facility could in principle be built in an unexceptional warehouse-sized building. All the chemicals involved are widely available, used for a variety of other industrial purposes. Significant engineering skill and experience would be required, however. The workers at such a simple facility would probably receive radiation doses large enough to increase their risk of cancer, but not to cause immediate illness. This might not be a sufficient deterrent, however. By far the greatest difficulties would arise from the need, because of the radioactivity, to carry out all the main steps with remotely operated equipment.

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If the facility had been built ahead of time and the procedures practiced (though without actual spent fuel available for realistic tests), *in principle* the time needed to separate the requisite amount of material might be only days or weeks if all went according to plan. In practice, however, the time needed is likely to be longer. The IAEA's Standing Advisory Group on Safeguards Implementation has estimated that the time required to convert plutonium in spent fuel into a weapon would be one to three months, compared to seven to ten days for metallic plutonium.

Although the processes and technology of reprocessing are unclassified, the experience gained in actually operating reprocessing plants is not widely available. As with other chemical engineering processes, many countries' initial attempts at reprocessing have encountered unexpected difficulties. Thus, there would be no guarantee of success in separating plutonium without substantial testing and practice. Such testing would greatly extend the time required.

The proliferation risk posed by spent fuel grows with time as its radioactivity becomes less intense. Fifteen years after leaving the reactor, the dose rate from a spent fuel assembly irradiated to a typical burnup would be more than 2,000 rads per hour at 1 meter from the center of the bundle, and ten times less than that after one year; 5 meters away, the dose would be only 200 rads, meaning that a person could stand 5 meters from such an assembly, unprotected, for more than an hour without receiving a lethal dose of radiation. After 15 years, the radioactivity declines by 50 percent every 30 years. How long it would take to reach the point at which remote processing, the largest single obstacle to plutonium recovery, would no longer be needed depends on how much radiation the workers in the facility would be willing to tolerate and what precautions were taken to protect them. Both the U.S. Nuclear Regulatory Commission and the IAEA consider materials emitting more than 100 rads per hour at 1 meter to be sufficiently self-protecting to require a lower level of safeguarding (though the adequacy of that standard should be reexamined). Spent fuel of typical burnup would take more than 100 years to decay to this dose rate.

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[1] Spent fuel could be stolen from reactor cooling ponds, for example, by using a large truck and crane, with personnel able to remain a considerable distance from the fuel at all times to reduce their radiation doses. Such an operation would be quite observable, however, and the thieves would almost certainly be pursued.

[2] See W.G. Sutcliffe and T.J. Trapp, eds., "Extraction and Utility of Reactor-Grade Plutonium for Weapons," Lawrence Livermore National Laboratory, UCRL-LR-115542, 1994 (S/RD). See also U.S. Congress, General Accounting Office, *Quick and Secret Construction of PlutoniumReprocessing Plants: A Way to Nuclear Weapons Proliferation?*, General Accounting Office, EMD-78-104 (Washington D.C.: U.S. Government Printing Office, October 6, 1978).

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Choice of a reactor option would not necessarily reopen the issue of reprocessing, however, since the spent fuel standard can easily be met by once-through fuel cycles. (Only the use of reactors for plutonium "elimination" would require reprocessing.) Whatever is done with excess weapons plutonium, moreover, will affect only a small portion of the world's current and future plutonium inventory. For either the use or the disposal options, if the United States wishes to maintain a policy of generally discouraging separated plutonium fuel cycles, or if it wishes to make support for such cycles contingent on stringent safeguards and security measures, it will need to make a clear statement of how its choice fits within that broader context.

Non-Security Criteria. Protection of the environment, safety, and health (ES&H), along with public and institutional acceptability, are also essential criteria for all disposition options. Additional important criteria, described in Chapter 3, include the cost of the option, and its compatibility with other policies and objectives.

As noted elsewhere, however, the committee does not believe that the future of civilian nuclear power—which depends on economic, political, and technical issues outside the scope of this study—should be a major criterion for choosing among disposition options.

Tritium Production. Tritium production was not part of the committee's charge, and it has not examined alternatives for this purpose in detail. There is, however, no essential reason why plutonium disposition and tritium production need be linked, and there appear to be good arguments why they should not be.

At present, arms reductions are continuing at a rate of more than 5 percent per year, thus outpacing tritium decay. The reactor or accelerator capacity that would ultimately be needed to produce enough tritium to support an arsenal of the size currently projected is many times less than that needed to carry out disposition of 50 tons of weapons plutonium over 20 to 40 years. Thus, tritium production capacity will be easier to provide than plutonium disposition capacity and should not bias consideration of alternatives for the latter purpose. At such low production levels, accelerator production of tritium may be preferred over reactor production, and purchase could also be considered, though that would raise other policy issues.

From a policy perspective, producing new weapons materials in the same reactor being used for disposition of other weapons materials would have important ramifications for the nonproliferation and arms reduction regimes, local political support, and safeguards. In particular, President Clinton's commitment to put excess U.S. fissile materials under International Atomic Energy Agency (IAEA) safeguards would mean that if tritium production and plutonium disposition were carried out in the same reactor, either the tritium production reactor would have to be under IAEA safeguards or the plutonium would have to be removed from safeguards during disposition.

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Cost savings from carrying out both plutonium disposition and tritium production using the same process and facilities would probably not be large, and must be balanced against the complications outlined above. In summary, the committee believes that the potential for producing tritium should not be a major criterion for deciding among plutonium disposition options.

Figure 6-5, at the end of the chapter, summarizes in a matrix format the committee's judgment of how the various options rate under these criteria, with the main options representing the rows and the criteria the columns. Most of the remainder of this chapter is devoted to a description of the three major categories of options for long-term plutonium disposition, directed toward supporting the judgments in that chart.[5]

THE OPTIONS

Indefinite Storage

Indefinite storage could be pursued for several decades with costs and ES&H risks substantially lower than those of the other disposition options. New storage facilities would eventually be required, as would plutonium processing to deal with long-term deterioration of the pits. This would increase costs and ES&H risks, but these might still remain below those of most other disposition options. This option would also offer the greatest flexibility for later use of the plutonium.

A decision to store excess weapons plutonium indefinitely, however, would have a number of important liabilities. Of all long-term disposition options, indefinite storage would entail the highest risk of breakout and of proliferation by theft from the storage site.

Prolonged storage of large quantities of excess fissile materials, particularly in the form of weapons components, would send the message that the nation storing these materials was maintaining the option to rebuild its Cold Warera nuclear arsenal. Such perceptions could politically undermine efforts to pursue deeper reductions, to bring other nations into the arms reduction regime, and to maintain and strengthen the nonproliferation regime. Finally, plutonium storage without a designated end point would be difficult to justify to the public; communities in which plutonium is now stored have demanded and received assurances that they will not become the final resting grounds for this material.

[5] The reactor, accelerator, and vitrification options are discussed in more detail in *Management and Disposition of Excess Weapons Plutonium:Report of the Panel on Reactor-Related Options*, (Washington, D.C.: National Academy Press, 1994), while the other disposal options are considered in Appendix C. References for the descriptions of the various options in this chapter can be found there.

The description of the reactor options that follows is more extensive than that of the disposal options, in part because there are more variants of the reactor options, and in part because the issues involved in the reactor options are somewhat better understood; the relative lengths of the discussions, however, should not be construed as indicating the committee's preferences.

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For these reasons, poststorage disposition options should be explored, decided on, and carried out expeditiously. Continuing to store this material indefinitely would mean either (1) a decision that the security risks of the processing steps involved in any of the other options were too great for the foreseeable future, particularly given conditions in Russia; (2) a rejection of the disposition options proposed to date, and an expectation that better options would be developed in the future; (3) a failure to decide and act; or (4) an explicit decision to maintain a capacity to rapidly reincorporate this plutonium into nuclear weapons.

More exotic approaches to storage, designed to reduce the liabilities just described, have been proposed. For example, plutonium pits in casks might be placed in monitored, retrievable storage in a mined geologic repository.[6] As described below, such approaches would not be acceptable for long-term disposal. Although they might have some advantages for intermediate storage, they would do little to reduce the breakout threat or the political hazards of prolonged storage, and the risk of theft can be addressed by other means at existing or planned storage sites.

Minimized Accessibility Options

Reactor Options

A wide range of reactors—existing, evolutionary, and advanced—could use weapons plutonium in their fuel (for an illustration of the general steps involved, see Figure 6-2).

By doing so, they could seek to meet the "spent fuel standard" described above, typically by using the fuel in a "once-through" cycle, or they could seek to eliminate the plutonium nearly completely, by repeatedly reprocessing and reusing it. The spent fuel options are described here, while the elimination options are described later, in a section of their own.

In the spent fuel approach, a substantial fraction of plutonium would remain in the spent fuel. The main goal of this approach is not so much to *destroy* the plutonium—by fissioning the plutonium atoms or transmuting them into other elements—as to contaminate it with highly radioactive fission products, requiring difficult processing before it could be used in weapons. In addition, this option would shift the isotopic composition of the plutonium from "weapons-grade" toward "reactor-grade." As noted in Chapter 1, however, formidable explosives can still be made from reactor-grade plutonium.[7]

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[6] See Luther Carter, "The Other Side of the Mountain," *WashingtonPost*, August 22, 1993, p. C4.

[7] Weapons-grade plutonium, produced by comparatively brief irradiation of uranium in reactors, typically has some 93 percent plutonium-239 (Pu-239) and 6 percent Pu-240; reactor-grade plutonium contains much larger fractions of Pu-240 and other isotopes. See "Reactor-Grade and Weapons-Grade Plutonium in Nuclear Explosives," Chapter 1, p. 32.

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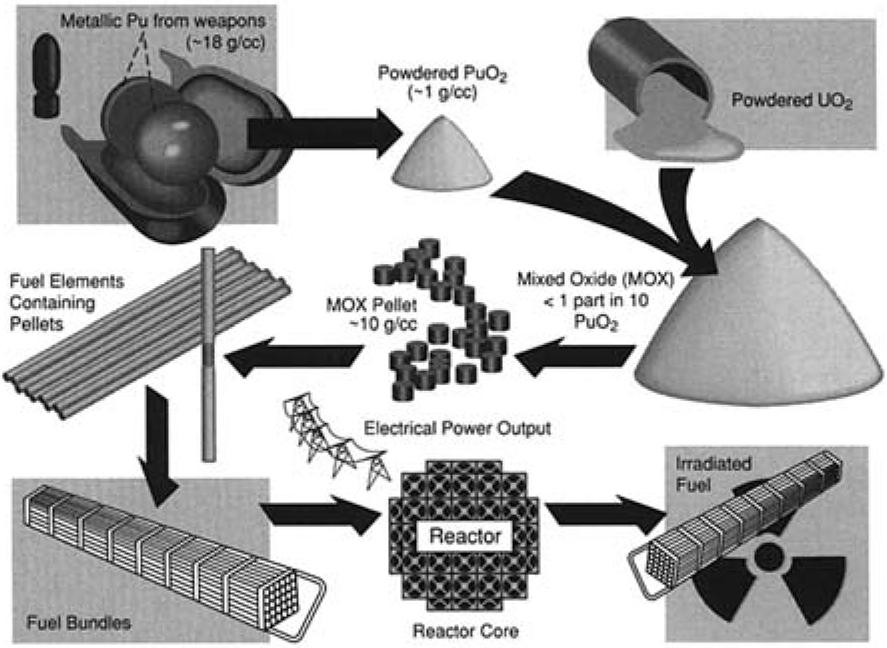

FIGURE 6-2 Steps in the spent fuel option
Source: Redrawn from The Department of Energy's (DOE's), *PlutoniumDispositionStudy*(Washington, D.C.: U.S. Department of Energy, 1993).

In all the once-through options, enough plutonium would remain in the fuel to require safeguards comparable to those employed for typical commercial spent fuel. For all plutonium destruction fractions achievable in such a once-through cycle (roughly, between 20 and 80 percent), the quantity of plutonium remaining in the spent fuel would be substantial—between 10 and 40 tons remaining from a disposition campaign beginning with 50 tons of weapons plutonium. Although substantial, these residual quantities would be small compared to the growing world stock of civilian plutonium in spent fuel. Thus, within the range of plutonium destruction achievable without reprocessing, *the specific destructionfraction would have little impact on overall security risks*, either those of the remaining plutonium in this spent fuel or those of the global stock of plutonium in spent fuel.

Another possibility, discussed as a separate option in some studies, is to use much briefer irradiation of the weapons plutonium—typically for only a few months—to "spike" the plutonium with fission products, creating some radiation barrier to its use in weapons more rapidly (or with fewer reactors) than would be possible in the spent fuel option. In itself, this approach would not meet the spent fuel standard, and hence would not provide an adequate barrier to use of the material in weapons over the long term. But since the resulting

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partly used fuel could be reused in reactors, this spiking approach might be considered as a possible step along the road to the spent fuel option.

Existing, Newly Built, and Advanced Reactors for the Spent Fuel Option. Either existing reactors (possibly with modifications) or newly built reactors constructed for the purpose could process excess weapons plutonium into spent fuel. New reactors built for this purpose, particularly those of more advanced design, would require more time and money. The initial capital cost of a new nuclear reactor amounts to billions of dollars, and such reactors would take many years to build—particularly in the United States, where nuclear construction has encountered intense opposition in recent years, and no reactors have been ordered since 1978. The number of nuclear reactors already available in the United States would not be a limiting factor for this mission; fuel fabrication capacity and political, institutional, and licensing issues will be the pacing elements. For the conversion of weapons plutonium to spent fuel, new reactors would not offer sufficient advantages to offset their disadvantages in time, cost, and uncertainty —unless institutional and political obstacles to the use of existing or partly built reactors were to prove insurmountable.

If that were to be the case, a new reactor could be built on a government-owned site, thereby potentially simplifying the licensing and public acceptance issues. In that case, the reactor chosen should be one of sufficiently known design to avoid unnecessary technical uncertainties and licensing delays. For transforming weapons plutonium into spent fuel, the more advanced designs do not offer sufficient advantages to overcome their liabilities of cost, timing, and uncertainty.[8] The same conclusion holds for new fuel types for existing reactors (such as so-called nonfertile fuels, which do not contain uranium-238 (U-238) and therefore do not produce more plutonium as they are burned).

Research and development on advanced reactors and fuel types are of interest only in the context of the future of nuclear electricity generation, including the minimization of security and safety risks. As part of that future, they

[8] These cost, timing, and uncertainty issues are described in more detail in *Management and Disposition of Excess Weapons Plutonium:Report of the Panel on Reactor-Related Options (op. cit.).* Past analyses have reached similar conclusions regarding these liabilities of more advanced reactor designs. The Department of Energy's (DOE's) *PlutoniumDisposition Study* (Washington, D.C.: U.S. Department of Energy, 1993) for example, warned that advanced concepts such as liquid metal reactors and high-temperature gas-cooled reactors were "significantly less mature than the light water reactors," which "would be expected to result in greater development and deployment costs and schedule risks." (Vol. 1, p. 4). Similarly, a study prepared for DOE in February 1993 estimated that the total costs of such advanced systems (measured in net dollars per kilowatt-hour) would be significantly higher. (See Ronald P. Omberg and Carl E. Walter, "Disposition of Plutonium from Dismantled Nuclear Weapons: Fission Options and Comparisons," Lawrence Livermore National Laboratory, February 5, 1993, UCRL-ID-113055, p. 19.) The committee was also influenced by the National Research Council report on the future of nuclear power, which rated these advanced systems as "low" for economy, market suitability, maturity of development, and licensing, while evolutionary light-water reactors were rated "high" in all of these respects, see National Research Council, *Nuclear Power: Technical and Institutional Options for theFuture* (Washington, D.C.: National Academy Press, 1992), p. 105.

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Management and Disposition of Excess Weapons Plutonium

may offer the possibility of pursuing the "elimination" approach in the long term, not only for weapons plutonium but also for the much larger quantities of civilian-sector plutonium. *Advanced reactorsshould not be specifically developed or deployed for transformingweapons plutonium into spent fuel, because that aim can be achievedmore rapidly, less expensively, and more surely by using existingor evolutionary reactor types*. In saying this, the committee does not intend to recommend either for or against the development and deployment of advanced reactors for commercial electricity production, which is beyond the scope of its charge. If new reactors are built for commercial power production, and if by that time the disposition of weapons plutonium has not been completed, their possible contribution to that goal should be reviewed in the context of the alternatives available at the time.[9]

U.S. law prohibits the use of commercial nuclear facilities for military applications. There is no prohibition, however, on the use of military material for civilian purposes, the situation examined here. Indeed, use of low-enriched uranium (LEU) from formerly military highly enriched uranium (HEU) stocks in civilian reactors is already planned; use of fuels produced from plutonium stocks is different in specifics, but not in principle.

In Russia, the adequacy of existing reactors for the weapons plutonium disposition mission is not as obvious as in the United States, as few Russian reactors are safe enough to continue operating over the long term. But, as described below, the VVER-1000 LWRs—the safest of the Russian reactors—would be sufficient to carry out this mission. Here, too, if new reactors must be built for the plutonium disposition mission, for political or institutional reasons they should be existing or evolutionary types rather than advanced types.

As noted above, long-term disposition options may differ in significant respects in Russia and the United States. In what follows, the use of each country's own reactors is considered first, followed by other nations' reactors that might also be used. The description of the use of U.S. plutonium in U.S. LWRs will be the most detailed, with other options described in significant part by comparison to that base case.

U.S. PLUTONIUM IN U.S. LWRs

Feasibility and Reactor Requirements. Commercial reactors of the types currently operating in the United States, known as light-water reactors, offer the technical possibility of transforming excess weapons plutonium into spent fuel within a few decades. Such a plutonium disposition campaign could probably begin within roughly a decade, paced by the need to provide a plutonium fuel fabrication capability (no such facility is currently operational in the United States) and a variety of institutional issues, including licensing and

[9] Advanced reactor options for production of spent fuel are described in more detail in *Management and Disposition of Excess Weapons Plutonium:Report of the Panel on Reactor-Related Options* (op. cit.) and are considered only briefly below.

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public acceptance (no U.S. LWRs are currently licensed to handle plutonium fuel). Once started, the campaign could be completed within 20-40 years, paced by the number of reactors participating (which involves important trade-offs between the advantages of processing plutonium more rapidly with more reactors and the associated risks of greater transport and more widely dispersed handling of plutonium); whether the reactors use plutonium in one-third or in all of their reactor cores; the fraction of plutonium incorporated in the fuel; and the average length of time the fuel is kept in the reactor. A subsidy would be required, compared to providing the same electricity from the same reactors with standard LEU fuel (an issue discussed in more detail below).

For this purpose, plutonium would be mixed with natural or depleted uranium to produce a "mixed-oxide" (MOX) fuel, which typical commercial LWRs could use in one-third of their cores without major modification. The technical feasibility of using such fuels is amply demonstrated. Indeed, a number of reactors in Europe are operating with one-third MOX cores today (with fuel performance demonstrated to be comparable to that of uranium fuel), and more reactors are slated to begin using such fuels in both Europe and Japan in the near future.

Using one-third MOX cores, U.S. LWRs, with typical capacities of about 1 gigawatt-electric (GWe) each, could transform 50 metric tons of excess weapons plutonium into spent fuel—substantially similar to what is already produced by these reactors—in 150 to 250 reactor-years of operation.[10] Put another way, 5-8 GWe of reactor capacity (out of a total U.S. LWR capacity of about 98 GWe) would have to be used to accomplish the job in 30 years.

Using MOX in all of the reactor core would cut the number of reactors or the time required by a factor of three. Because the nuclear characteristics of plutonium differ from those of uranium, however, most current-generation LWRs could use MOX in their entire reactor cores only if they were significantly modified, by adding more control rods and possibly increasing the effectiveness of each rod. To modify already operating reactors in this way would require safety review and a substantial shutdown period, and the costs have not yet been estimated. There are, however, three operating U.S. reactors and one unfinished reactor, called System-80s, that were designed with the inherent capability to handle a full core of MOX fuel—though such operation is not included in their current licenses and a detailed safety review to assess the adequacy of the design would be required.[11]

In addition to the fraction of the reactor containing MOX, two other factors determine how many reactor-years would be needed to process a given amount

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[10] For example, LWRs of 3000-MWt (thermal megawatts) capacity running at a capacity factor of 70 percent, using one-third MOX fuel containing 2.5 percent plutonium by weight, kept in the reactor to an average burnup of 30,000 megawatt-days per metric ton of "heavy metal" in their fuel (30,000 MWd/MTHM), would process 208 kilograms of weapons plutonium per reactor-year, requiring 240 reactor-years to process 50 metric tons of plutonium, or eight reactors operating for 30 years.

[11] These are the three reactors at Palo Verde, Arizona, and the incomplete Washington Nuclear Project 3 (WNP-3) reactor in Washington State, discussed in more detail below.

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of plutonium: the percentage of plutonium in the MOX, and the length of time the fuel remains in the reactor (known as the *burnup*, measured in megawatt-days per metric ton of "heavy metal" (uranium or plutonium) in the fuel—MWd/MTHM).[12] For example, the System-80 reactor could process 50 metric tons of excess weapons plutonium in 60 reactor-years using a 100 percent MOX core with a relatively low enrichment of 2.5 percent and an average burnup of 31,000 MWd/MTHM; increasing the initial enrichment to 6.8 percent (roughly the maximum likely to be possible without requiring changes to the reactor) would allow the job to be done in 30 reactor-years, even if the burnup were increased to 42,000 MWd/MTHM.

The safe use of enrichments of 6-7 percent requires neutron-absorbing materials such as erbium (known as "burnable poisons") to help control the nuclear chain reaction; this too would require safety review. In addition to reducing the number of reactor-years required, such high enrichments would reduce overall fuel fabrication costs, as discussed below.

Fuel Fabrication. Providing adequate plutonium processing and MOX fuel fabrication capability would be an important pacing factor for processing excess weapons plutonium in U.S. LWRs.

Plutonium pits would have to be shipped from Pantex (where no plutonium processing capability yet exists) to a site capable of disassembling the pits and converting the resulting metal to plutonium oxide. No facilities for carrying out pit processing on the required scale are currently operating, but facilities at Savannah River, Los Alamos, and possibly elsewhere could be modified for this purpose, and as mentioned in Chapter 5, new technologies for efficient pit conversion are being developed at the national laboratories.[13]

Because plutonium is more radioactive and requires greater safeguards than low-enriched uranium, facilities for fabricating uranium fuel cannot simply switch to fabricating plutonium fuel; special MOX fabrication facilities must be provided. Although there are no MOX fabrication facilities currently operating in the United States, a nearly complete facility designed to produce plutonium fuel for experimental fast reactors at the Hanford site in Washington State, known as the Fuel and Materials Examination Facility (FMEF), could be modified to produce MOX fuel for light-water reactors. Although further study of this modification is required, the committee has received estimates (which may be optimistic) that this facility could be modified to produce 50 metric tons of fuel per year or more (containing roughly 3 metric tons of weapons plutonium, at 6-7 percent enrichment), while meeting current safeguards and ES&H standards, within roughly five years of receiving a go-ahead, for a cost in the range of $75-$150 million. Alternatively, a new plutonium fuel fabrication facility

[12] The reactor's capacity factor—its average output in a given period divided by its rated capacity—also has some impact. Most well-run reactors have capacity factors in the range of 60-80 percent for LWRs, and as high as 90 percent for CANDUs (which do not have to shut down to refuel).

[13] This step—which is necessary for most, but not all, of the disposition options—will probably cost of order $100-$300 million for 50 tons of plutonium.

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could be built; estimates provided to the committee (which are almost certainly optimistic) indicate that such facilities could be built for between $400 million and $1.2 billion, depending on their capacity. Siting, building, and licensing such a facility would probably require a decade or more.

Reactor and Institutional Options. Many variants of such a U.S. MOX-burning plan can be imagined, involving different facilities and different institutional arrangements (such as a mix of government and private involvement).

As noted earlier, if possible it would be desirable to use existing or partly completed LWRs for this mission, to avoid the delays and costs of building new facilities. Existing U.S. commercial nuclear reactors are owned and operated by private utilities. If these reactors were to be used for plutonium disposition, several institutional options suggest themselves:

- provision of plutonium fuel to utilities by the government, at the same or lower cost as the utilities pay for equivalent low-enriched uranium fuel (the government absorbing the expected extra costs of fabricating plutonium fuel);
- government acquisition of reactors, turning them into government-owned plutonium disposition sites; or
- a mix of private and government roles in control and management of the sites. For example, the government might acquire the reactors and turn them into a federal site, managing them in partnership with private entities. The private entities would manage the production and sale of electricity, because the federal government is barred by the Atomic Energy Act from directly selling electricity from nuclear facilities on private markets. The private entities might provide all or part of the initial investment, reducing the upfront capital cost to the government.

Given the international implications of an excess weapons plutonium disposition program, and the need to set stringent standards for security and safeguards, a government role is required. Moreover, the problem of gaining the necessary approvals and licenses for MOX reactor operations might become easier if the sites were federal facilities—either sites already owned and operated by the government, or commercial reactors acquired and turned into federal sites for the plutonium disposition mission. The following are a few of the most obvious specific candidates for this role.

Operating Reactors at Palo Verde. Three System-80 LWRs are operational at the Palo Verde site in Arizona, owned by a private utility. As noted above, with license amendments these could operate with full-MOX cores without modification. If the utility agreed to participate, the federal government could cover any additional costs in using government-furnished MOX fuel and could provide the necessary new safeguards and security at the site, while the utility could otherwise continue to operate the reactors much as they are operated today. Additional financial incentives might be required to convince the utility to

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undertake the new political and licensing burdens involved. Using these reactors would limit handling of "fresh" plutonium and MOX fuel to two sites—one where the MOX fuel would be fabricated (presumably a site within the nuclear weapons complex) and the Palo Verde reactor site. Utility and public reactions to this concept have not been explored.

Partly Completed Reactors in Washington State. Two partly completed nuclear reactors exist in Washington State: Washington Nuclear Project (WNP) 3 is a System-80 reactor, 75 percent complete, in the western part of the state, roughly 150 miles from the Hanford nuclear-weapons complex reservation; WNP-1, 63 percent complete, is not a System-80 and would have to be modified to handle a full core of MOX as its construction was completed, but it has the advantage of being physically located on the Hanford reservation. One or both of these reactors could be acquired, completed, and operated by the federal government (possibly in cooperation with a private entity) for the plutonium disposition mission. If the MOX fabrication capability at Hanford were used, this would have the significant advantage of confining all plutonium handling to two federal sites in the same state (or even a single large site, if only the WNP-1 facility on the Hanford reservation were used). A consortium of private companies has put forward a proposal for a government-private partnership to pursue this approach.[14]

Acquisition of Other Existing Facilities: If both the Palo Verde and the WNP facilities were unavailable or faced insurmountable licensing or public approval difficulties, there are several other U.S. reactors that utilities may be willing to provide to the government, either because they were never completed

[14] This concept, known as the "Isaiah Project," is being put forward by a team consisting of Battelle, Science Applications International Corporation, and Newport News. (Briefing for NAS Panel on Reactor-Related Options for Disposition of Weapons Plutonium, May 7, 1993.) In their proposal, the private consortium they would set up would acquire and complete the reactors at its expense (deeding ownership of the reactors to the government), and receive revenue to pay for debt service and profit. The government would pay for reactor operations, fuel fabrication, storage, and disposal, and provide a contractual guarantee of particular quantities of steam for electricity production. Advocates for this concept have emphasized the possibility that the private entity could borrow several billion dollars against the future revenues of the project, which could be provided to the government to finance other endeavors, such as assistance for plutonium disposition in Russia. This is misleading, however, as future costs assigned to the government in this concept would come to substantially more than the sums that could be borrowed. Hence, as with other approaches, the project would ultimately involve a net discounted present cost to the government, not a net discounted present value. Borrowing against future revenue, with the accompanying promise of large future government expenditures, would simply amount to deficit financing by other means. This point is equally applicable to other approaches involving private financing of initial capital costs in return for government promises of later subsidies.

Another operating reactor, WNP-2 is also located on the Hanford reservation, and like WNP-1, could be modified to handle a full core of MOX fuel. This would require shutting down an operating reactor for modification, with the accompanying cost of lost revenue, and the utility that owns the reactor would have to be persuaded to allow its use for this purpose. This option, however, would have the significant advantage of providing two reactors and a fuel-fabrication facility on a single nuclear-weapons complex site. The time and cost for modifying and licensing WNP-2 might turn out to be less than the time and cost of completing and licensing WNP-3.

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or because their continued operation is becoming economically uncompetitive.[15] These could be acquired, modified for full-MOX cores, and used much as the WNP reactors might be.

Principles for Institutional Arrangements. The specifics of such institutional arrangements require further study, but several basic principles suggest themselves:

- As noted above, the government should have a strong role, to ensure that the approach fits with broader national policies relating to arms reduction and nonproliferation, that adequate security and safeguards are maintained, that any necessary openness to international inspection is maintained, and that appropriate ES&H standards are met.
- The number of sites should be minimized, to consolidate monitoring and safeguards functions and reduce the risks of plutonium theft.
- The sites should probably be federal facilities (either already owned by the government, or acquired for this purpose), to ease the task of gaining the necessary approvals and licenses and of maintaining the security and international transparency mentioned above.
- Any increase in government competition with private electricity generation should be minimized to the extent possible.
- If private investment can genuinely reduce government costs and up-front federal capital investments, it should be encouraged. But assessments of such possibilities must include realistic appraisals of all likely future costs and revenues, and the financial risks of government commitments to future subsidies or operations.

Approvals and Licenses. In addition to fuel fabrication, approvals and licenses are important pacing factors. The United States initiated a licensing process for using MOX in LWRs in the 1970s (the Generic Environmental Statement for Mixed Oxide fuel, or GESMO), but this process was terminated when President Carter decided to end government support for the plutonium fuel cycle. Although there do not appear to be fundamental obstacles to licensing a small number of U.S. reactors to handle MOX, particularly if no reprocessing is involved, it is likely to take the better part of a decade before the requisite fuel fabrication and reactor sites are licensed and operational. Substantial public controversy would almost certainly attend siting and construction of a plutonium fuel fabrication facility, and the use of plutonium fuel in U.S. reactors.

There are important open questions concerning the licensing process for the various plutonium disposition facilities. Currently, the Nuclear Regulatory

[15] By some estimates, there may be a dozen or more reactors in the United States that are in danger of being shut down well short of their design lives because utilities have other, more economical alternatives available. These reactors would be prime candidates for acquisition by the government for the plutonium disposition mission.

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Commission (NRC) regulates only civilian nuclear power plants. The Defense Nuclear Facilities Safety Board (DNFSB) was established by Congress to provide a form of regulatory oversight for the Department of Energy (DOE) weapons facilities, but it is an advisory body and does not have regulatory power. If one or more nuclear plants for plutonium disposition were owned by DOE, the DNFSB could be asked to provide oversight. Nevertheless, it is virtually certain that any such facility would have to meet NRC safety standards, and the committee believes this is desirable. Gaining approval by the DNFSB would probably take even longer than gaining NRC licenses, because the DNFSB staff is much smaller than the NRC's and has less regulatory experience. Moreover, DNFSB oversight might be more likely to be challenged in court. Licensing a MOX fabrication facility would also be time-consuming; it, too, might be done under either the NRC or the DNFSB. Under the National Environmental Policy Act (NEPA), Environmental Impact Statements (EISs) are likely to be required for several of the facilities, and the time required to prepare these and obtain approval for them would be substantial.

Public approval in the areas near the relevant facilities will also be a critical factor. Problems of public approval and licensing could be lessened somewhat if both the plutonium fuel fabrication facilities and the reactors handling MOX fuels were on federal sites. This is the main argument for building new reactors at existing DOE sites, rather than relying on existing civilian reactors. There is a good chance, however, that these problems could be addressed at some existing reactors, particularly if they were acquired as new federal sites. Chances for local public approval for the operation of FMEF for MOX fuel fabrication or the construction of new MOX facilities might be improved if the jobs associated with the fabrication plant and those that might be associated with reactor modification and operation were provided in the same area.

Safeguards and Security. The discussion to this point has focused primarily on feasibility and timing. Another important criterion identified above is safeguards and security, enumerated under the "risks of handling." An agreed system of safeguards and security, as part of the overall regime for fissile material storage and management discussed in Chapters 4 and 5, should be adopted.

Given the stringent security procedures and the low incidence of terrorism in the United States, risks during transportation are substantially lower in the United States than in Russia at the moment. The scale of transport required will depend to a great degree on the number of sites, and in particular on whether conversion of pits to oxides, fuel fabrication, and the relevant reactors would be located at the same site or at several widely dispersed locations. The number of sites at which this plutonium is handled, the number of shipments of plutonium, and their length should be minimized to the extent possible, to limit the risks of theft.

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Once the plutonium is in the form of bulk oxide, rather than individually packaged pits, precise accounting to detect any diversion will become considerably more difficult. This will be a particular problem at the fuel fabrication facility, where the accounting system will need to have the capability for timely detection of diversion or theft of even a very small percentage of the facility's throughput. The IAEA and the EURATOM (European Community's Safeguarding Agency) have been working for years (with assistance from the U.S. Los Alamos National Laboratory) to develop new techniques for safeguarding such large plutonium bulk-handling facilities because similar large facilities for civilian plutonium processing are scheduled to open soon in Europe and Japan. Nevertheless, some of these techniques are still in development, and it is doubtful that material accounting alone will be able to guarantee that diversion of enough plutonium to make a bomb could be detected within days. It will probably not be possible to achieve the stored weapons standard of accounting when dealing with complex, multistage processing of plutonium in bulk form. Therefore, in addition to stringent material accounting, there should be extensive containment, surveillance, and security measures to ensure that no plutonium leaves the site without authorization.

Indirect Impact on Civilian Fuel Cycle Risks. As noted above, policymakers considering plutonium disposition options should be aware that the use of U.S. weapons plutonium in U.S. LWRs could be seen as a significant change in U.S. policy, which has been not to pursue a plutonium fuel cycle. Such a shift could have an impact involving decisions on civil plutonium policies in Europe, Japan, and elsewhere.

Cost. As noted earlier (see "The Value of Plutonium," Chapter 1, p. 24), the cost of this approach depends on a large number of assumptions concerning figures that are uncertain—and also on how one conceptualizes the calculation. The required subsidy for using MOX fabricated from weapons plutonium rather than LEU in existing LWRs is likely to range from several hundred million to a billion dollars. If reactors had to be built, completed, or modified, or if the differences between LEU and MOX spent fuel involved higher disposal costs for MOX, those expenses would have to be added to this figure.[16]

Environment, Safety, and Health. With appropriate modifications, it should be possible to operate U.S. LWRs with full-MOX cores while meeting the same safety standards that pertain to LEU fuel. The plutonium processing necessary for this option (pit conversion and fuel fabrication) would inevitably result in wastes, risks of accident, and worker hazards. Careful design and the application of sufficient resources, however, should enable these facilities to comply with current regulatory standards. MOX operations have been demonstrated

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[16] For a more detailed cost analysis of this option and other reactor-related options, see *Management and Disposition of Excess Weapons Plutonium:Report of the Panel on Reactor-Related Options*, op. cit.

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in Europe, but have not yet been undertaken in the U.S. regulatory environment.[17]

The spent fuel resulting from this option would be similar in most respects to ordinary LEU spent fuel, but there are important differences.[18] MOX spent fuel will contain more plutonium than typical spent fuel (raising potentially greater criticality concerns after eventual emplacement in a geologic repository) and will emit more heat for a longer time (which has an impact on the repository volume required to hold a given number of fuel assemblies). The possibility that the somewhat different chemistry of the MOX spent fuel would affect long-term rates of release of radioactive materials in the repository would also have to be examined. This different spent fuel would have to be separately licensed as an acceptable waste form for geologic disposal, meaning additional costs and potentially additional delays. Once these issues are addressed, however, it should be possible to store and dispose of MOX spent fuel as safely as LEU spent fuel. If the reactors used for this purpose would have operated with LEU in any case, the total amount of spent fuel to be disposed of in a geologic repository would not be increased as a result of plutonium disposition; even if reactors were operated specifically for plutonium disposition, the total amount of added spent fuel would be a small fraction of the planned capacity of the first U.S. repository.

The Spiking Option. To "spike" the plutonium more rapidly than it could be processed into spent fuel would require a larger fuel fabrication facility (implying a higher capital cost) and more frequent reactor shutdowns for refueling (implying more lost revenue). Expanded fuel storage capacities at the reactor sites would also be required, to handle the fuel between the time when it was spiked and when it was recycled into the reactor to finish burning it to spent fuel. Hence, the costs of the spent fuel option would increase significantly if spiking were used as a first step. In addition, the radioactive exposures that might be incurred by workers in reintroducing the spiked fuel into the reactor would require careful examination. In the committee's judgment, the security for the material that could be gained by this more rapid but less extensive irradiation could be achieved more simply by providing appropriate security at the plutonium storage site; given its substantial costs, the spiking step on the path to the spent fuel option in LWRs is probably not worthwhile.

Summary. Processing weapons plutonium to spent fuel in existing U.S. LWRs is technically feasible. The time needed to provide fuel fabrication capability and acquire the necessary approvals and licenses would probably be 8-10 years or more. Given favorable safety reviews, the use of full-MOX cores

[17] For a more detailed discussion of the environment, health, and safety issues associated with the use of plutonium in LWRs and other types of reactors, see ibid.

[18] Like LEU spent fuel, this spent fuel would be stored for a period and then placed in a geologic repository. A U.S. repository is not expected to open before at least 2010, and that date remains highly uncertain.

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appears clearly preferable to one-third MOX cores. No insurmountable safeguards or ES&H obstacles appears to confront this option. The subsidy required to use plutonium rather than uranium in U.S. reactors would be between several hundred million and one billion dollars, not counting costs of reactor modifications, approvals, or additional costs of spent fuel disposal.

Advantages: Technically demonstrated; moderate cost; moderate timing; clearly meets the spent fuel standard.

Disadvantages: Safeguards and security issues in plutonium handling and transport; likely public controversy over plutonium processing, fabrication, transport, and use; possible impact on other countries' civilian plutonium programs contrary to existing U.S. plutonium fuel policies.

Conclusion: This option is a leading contender for long-term plutonium disposition.

Major Outstanding Issues: Although the use of MOX fuels in LWRs is technically demonstrated, further study of the following technical issues is required:

- confirming the safety of System-80 reactors operating with full MOX cores, and investigating the possibility of modifying other existing LWRs for full-MOX operation (including the specifics of the modifications that would be required, the likely shutdown time required, the cost of modification, and the likely licensing issues);
- examining the capability of the Hanford FMEF facility for LWR fuel fabrication, including cost and schedule for bringing it on-line, capacity, and ability to meet current safeguards and ES&H requirements;
- examining the cost and schedule for building new MOX fabrication facilities designed to meet safeguards, security, and ES&H requirements, for comparison to the FMEF option;
- examining the facilities, methods, costs, schedules, safeguards, and ES&H issues for large-scale processing of pits to oxide;
- examining technical issues in adapting MOX operations to the U.S. regulatory environment;
- assessing the acceptability of disposition of spent MOX fuel in geologic repositories;
- examining ES&H issues throughout the process, particularly in pit processing and fuel fabrication; and
- examining safeguards issues, particularly the ability to adequately safeguard MOX fuel fabrication facilities processing several tons of weapons-grade plutonium per year.

Further investigation of several institutional issues is also needed:

- licensing MOX fabrication facilities and reactors operating with plutonium fuels, including 100 percent MOX cores;
- addressing likely political opposition to plutonium fabrication and use;

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- arrangements for ownership and management of the facilities;
- arrangements for financing the operations, including the possibility of incorporating some private-sector financing;
- arrangements for safeguards and security, including international agreements in these areas; and
- the likely magnitude of the political impact of U.S. use of weapons plutonium in reactors on the use of separated plutonium fuels in other countries.

RUSSIAN PLUTONIUM IN RUSSIAN LWRs

The major differences in using Russian LWRs to process Russian excess weapons plutonium include much higher security risks in the disposition process, because of the current economic and political upheavals in the former Soviet Union; much lower availability of funds to finance the process; a smaller existing infrastructure of safe reactors; and different economic conditions, plutonium fuel policies, and licensing procedures.

Of the Russian reactors operating or under active construction, probably only the 950-MWe VVER-1000 light-water reactors, which are similar to Western designs, are adequately safe and have adequate capacity to carry out the plutonium disposition mission. Although the VVER-1000 reactors do not meet international safety standards, the consensus of foreign experts is that with planned upgrades they will be adequately safe, and that the Russian government will continue to operate them for the long term in any case. A substantial international program is under way to upgrade their safety. It does not appear that the use of MOX fuel would significantly degrade (or improve) the safety of these facilities. Earlier VVER designs and even more the RBMK graphite-moderated reactor design (used in the ill-fated Chernobyl reactor) do not meet acceptable safety standards and should not be considered for this mission; the Russian BN series fast reactors are discussed separately, below.

Russia has seven VVER-1000 reactors in operation, though some officials of the Russian Ministry of Atomic Energy (MINATOM) believe that because of varying designs, only the four most recent of these should be considered safe candidates for plutonium use. Several other VVER-1000s are under construction. Ten more operating VVER-1000s, and several additional facilities under construction, are located in Ukraine.

The capability of VVER-1000s to process weapons plutonium should be similar to that of most U.S. LWRs. Indeed, the modifications required for a full-MOX core might not be as extensive as in the case of U.S. reactors, because the neutron spectrum in these reactors is somewhat less energetic. None of the VVERs have yet operated with MOX fuel, however, and substantial safety analyses would be required.

MINATOM officials acknowledge that studies of MOX in VVER-1000s are just beginning and do not yet include the possible use of weapons-grade

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plutonium.[19] Because of the delays in commercializing fast breeder reactors that would consume plutonium separated by reprocessing, all other major reprocessing countries except Britain have decided to use plutonium as MOX in LWRs, to avoid the buildup of large stores of separated plutonium. Russia has not yet taken this route, preferring to save both military and civilian separated plutonium for eventual use in breeder reactors (see below). Russia already has some 25 tons of excess civilian separated plutonium, and more is building up every year, in addition to the excess military plutonium resulting from arms reductions. Some use of MOX in VVER-1000s is now being considered for the long term, however, during the transition to a breeder economy that MINATOM officials envision. Whether that transition will occur within the next several decades, and what will happen to the stored separated plutonium if it does not, remain controversial.

If full-MOX cores proved acceptably safe, with enrichments of perhaps 5 percent plutonium in the fuel, two VVER-1000 reactors could transform 50 metric tons of weapons plutonium into spent fuel in 30 years.[20] Each operational VVER-1000 is scheduled to be shut down for roughly one year for safety improvements under the ongoing program of international safety assistance. With enough lead time for proper design and preparation, the modifications necessary to handle a full-MOX core could be made during this period, without substantially extending the length of the shutdown. Alternatively, VVER-1000s scheduled for completion in the near future could be modified for this purpose as they are completed.

The public versus private issues in Russia are somewhat simpler, since MINATOM runs both the nuclear weapons complex and the civilian nuclear reactor industry. But as noted above, U.S. or international financial assistance may well be required if long-term disposition of excess weapons plutonium in Russia is to be accomplished in the foreseeable future. Just as private investment might help reduce up-front capital costs in the United States, private investment or loans from international financial institutions such as the World Bank or the European Bank for Reconstruction and Development might help

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[19] Evgeniy Kudriavtsev of MINATOM, for example, reported to the IAEA in April 1993 that "no serious investigations on military plutonium utilization in reactors of the VVER-type have been conducted in Russia," though he indicated that a future facility for fabricating MOX fuel for VVER-1000s is planned (see E. Kudriavtsev "Russian Prospects for Plutonium Accumulation and Utilization," unpublished paper presented to an IAEA meeting on problems of separated plutonium, April 1993). See also Yu. K. Bibilashvili and F. G. Reshetnikov, "Russia's Nuclear Fuel Cycle: An Industrial Perspective," *IAEA Bulletin*, Vol. 35, no. 3, 1993, and V.S. Kagramanyan, "Utilization of BN-800 Fast Reactors of Isolated Plutonium Being Accumulated in the Russian Federation," unpublished paper, April 1993.

[20] If, on the other hand, these reactors were limited to one-third MOX fuel, at a relatively low enrichment of 2.5 percent, nine reactors would be required to accomplish the same task. Since there are only seven operational VVER-1000s in Russia, either completion of additional reactors or use of some reactors in Ukraine would then be required. Given the uncertainty and conflicts surrounding Ukraine's nuclear activities, however, it would be preferable not to involve Ukrainian reactors in the use of weapons-grade plutonium.

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finance the operation in Russia, reducing the "line-item" costs that would have to be borne by any single government. These institutions are already considering helping Russia complete the VVER-1000 reactors under construction, to facilitate the shutdown of older unsafe reactors.

Fuel Fabrication. As in the United States, the time at which such disposition could begin would be paced by the availability of a MOX fuel fabrication facility. Although Russia has laboratory-scale MOX fabrication facilities, no production facility with the required capabilities is currently operational.

A MOX fabrication facility with an intended capacity of about 100 metric tons of heavy metal per year—enough to feed four VVER 1000s using full-MOX cores (processing as many tons of plutonium annually as the percentage in the fuel)—is reportedly roughly 50 percent complete at the Chelyabinsk-65 site. Completing the plant would require several years at a cost in the range of hundreds of millions of dollars. The standards of safeguards, security, and ES&H that this plant was designed to meet—or could practicably be modified to meet—are unknown.

Alternatively, a new MOX fabrication facility dedicated to the excess weapons plutonium disposition mission could be constructed. The German company Siemens has proposed using disarmament assistance to build a replica of the Siemens fabrication facility already built at Hanau (currently idle because of licensing disputes), which has a design capacity of 120 metric tons of heavy metal per year. Siemens estimates the cost of building such a facility in Russia at less than half a billion dollars, and believes that it could be accomplished within a few years. Similarly, the French state-owned company COGEMA has expressed interest in participating in providing MOX fabrication capability.

Approvals and Licenses. The political and institutional climate for plutonium use in Russia differs from that in the United States. In Russia, the government and the nuclear industry (controlled by MINATOM) are committed to a closed fuel cycle, including plutonium fuels, emphasizing fast breeder reactors. MINATOM wishes to save the excess weapons plutonium for eventual use as start-up fuel for future breeder reactors. Others indicate a desire to sell the excess plutonium. All maintain that weapons plutonium has value that must be exploited.

At the same time, the Russian public, after decades of government secrecy and the Chernobyl disaster, has become increasingly wary of all things nuclear, and distrustful of all government environment and safety assurances. Public resistance to plutonium use may therefore be significant. The regional and local authorities in Tomsk, for example (a major production site for weapons plutonium), have gathered sufficient strength in opposing the siting of a weapons plutonium storage facility there to call into question the viability of the plan. The regulatory agency that in principle is empowered to regulate nuclear facility siting and licenses, GOSATOMNADZOR, is seeking its role in the new Russia, and its future powers and attitudes toward plutonium use are uncertain.

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Thus, the time required to gain the required licenses and approvals in Russia is more uncertain than in the U.S. case, and could ultimately prove to be either longer or shorter.

Safeguards and Security. The risks of theft in transporting and processing plutonium in Russia under present circumstances appear high. Indeed, some analysts have argued that continued storage of the plutonium under high security until the Russian political and economic situation had stabilized would pose fewer risks than the processing and transport involved in the MOX option.

There are some important mitigating factors, however. As with the Hanford facility in the United States, the unfinished MOX fabrication facility in Russia is at a major nuclear weapons facility. In addition, the pattern in building the new VVER-1000 reactors has been to build several at a single site; at Balakovo, for example, there are four operating VVER-1000s, while another site has three. Thus, it might be possible to accomplish all processing of bulk plutonium at existing nuclear weapons complex sites, and all reactor use of plutonium fuel at one additional site. As in the U.S. case, all of the disposition steps should be subject to an agreed system of safeguards and security.

Indirect Impact on Civilian Fuel Cycle Risks. Assistance for using MOX in Russian reactors would inevitably provide a boost to the plutonium fuel cycle in Russia. There might also be some political impact in other countries whose civilian plutonium programs are controversial.

Russia also has some 25 tons of separated civilian plutonium waiting to be fabricated into fuel; some Russian officials and European analysts have suggested that they should fabricate this material into fuel before beginning the use of weapons plutonium, since civilian plutonium builds up radioactivity that makes it difficult to handle more quickly. Thus, disarmament assistance for construction of a MOX facility might in effect sponsor civilian plutonium use in Russia—and commercial competition for MOX fabricators in Europe.

Cost. Russian costs are uncertain, and no detailed analysis is possible with the information available. It is clear, however, that Russia has an overcapacity of low-cost LEU available for fueling its thermal reactors, which it is trying to market in the West to earn hard currency. It is also clear that significant up-front capital would be required to provide requisite plutonium fuel fabrication capability and to modify reactors to handle full-MOX cores. Therefore, substituting weapons plutonium for uranium in Russian LWRs would require a significant subsidy; the size of the subsidy would probably be in the range of hundreds of millions of dollars.

ES&H. To a large extent, the ES&H impact of plutonium disposition in Russian reactors would depend on the resources applied to mitigate these impacts and the standards set. Standards for ES&H protection in the former Soviet Union were low, and the resulting legacy of environmental devastation is

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now becoming clear. New ES&H policies are evolving in Russia, with uncertain prospects.

Summary. Processing weapons plutonium in Russian LWRs, operating and nearly completed, appears technically feasible. The time required to provide fuel fabrication capability and acquire the necessary approvals and licenses is highly uncertain. If safety reviews are favorable, the use of full-MOX cores appears clearly preferable to one-third MOX cores. The risks of theft or diversion of materials during disposition would be worrisome, given the current upheavals in Russia. ES&H issues are difficult to address in detail, given the evolving state of Russian standards. Similarly, costs are difficult to estimate; some subsidy to displace uranium fuel, which is currently very cheap in Russia, would be required.

Advantages: Technically feasible; moderate cost; moderate timing; meets the spent fuel standard.

Disadvantages: Major safeguards and security issues in plutonium handling and transport; supports infrastructure for civilian plutonium fuel cycle in Russia; possible impact on other countries' civilian plutonium programs contrary to U.S. fuel cycle policies.

Conclusion: This option is a leading contender for long-term plutonium disposition.

Major Outstanding Issues: The technical issues involved in this option are similar to those involved in the use of U.S. LWRs. Further examination is needed of:

- modifications required to ensure the safety of VVER-1000 reactors;
- the safety of operating VVER-1000 reactors with full-MOX cores and moderately high plutonium loadings, including the specifics of the modifications that would be required, the likely shutdown time required to make those modifications, the cost of modification, and the likely licensing issues involved;
- the capability of the unfinished Chelyabinsk MOX facility for LWR fuel fabrication, including cost and schedule for bringing it on-line, capacity, and ability to meet current safeguards and ES&H requirements;
- the cost, schedule, and capabilities of new MOX fabrication facilities, relative to the Chelyabinsk option; and
- issues, including ES&H and safeguards, concerning processing of pits to oxide.

The institutional issues are also similar to those in the United States, except that much greater safeguards risks and political and regulatory uncertainties are involved. Further study is needed of:

- arrangements to provide adequate safeguards and security in the current circumstances in Russia, including international agreements in these areas;

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- licensing and gaining local approval for the operations required in the evolving regulatory and political environment in Russia;
- arrangements for financing the operations, including the possibility of partial financing through disarmament assistance and loans from international financial institutions; and
- the likely magnitude of political impact of assistance for weapons-plutonium use on the use of separated plutonium fuels in other countries.

CANADIAN CANDU REACTORS

Commercial heavy-water-moderated reactors in Canada, known as CANDU reactors (for Canadian deuterium-uranium), appear to be capable, without physical modification, of handling 100 percent MOX cores. As in the LWR case, favorable regulatory review of the safety of their operation in this mode would be required. This option appears technically and economically feasible for either U.S. or Russian excess weapons plutonium, but major political questions remain open.

The current standard CANDU design could transform 50 metric tons of weapons plutonium into spent fuel in roughly 30 to 100 reactor-years of operation, depending on the initial enrichment of the fuel.[21] Canada has 20 CANDU reactors totaling about 14 GWe (46 thermal gigawatts; GWt); a number of these are at sites with as many as eight reactors at a single location. All the pacing elements for plutonium disposition based on existing CANDU reactors would be the same as those for using U.S. LWRs (fuel fabrication, licenses, the number of reactors, the enrichment and burnup of the fuel), except that there would be the added complication and uncertainty of seeking U.S.-Canadian agreement.

Compared to the use of U.S. LWRs, the use of CANDU reactors has both advantages and disadvantages. Advantages include:

Fewer Modifications for Plutonium Use: In normal CANDU operations with natural uranium fuel, more than half of the energy is provided by fissioning plutonium produced in the fuel as the reactor operates. As a result, adding plutonium to the initial fuel would represent a smaller change in the physics of the reactor core than in the case of LWRs. Moreover, the structure of the CANDU reactors allows plenty of space for added controls, and additional neutron absorbers could be dissolved in the heavy-water moderator used in the reactors.

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[21] A CANDU-6 reactor, with a capacity of 2,125 Mwt, operating at a capacity factor of 90 percent and an average fuel burnup of 16,000 would process 524 kilograms of plutonium per year if the initial plutonium content in the fuel were 1.2 percent (corresponding to amount required to provide the maximum fuel life the reactor manufacturer estimates current fuel designs could sustain without further development and testing). It could process more than 2,000 kilograms of plutonium per year if the initial plutonium content were 4.6 percent (the maximum enrichment the manufacturer estimates could be accommodated in existing CANDUs without modifications requiring some development). These rates correspond to 95 and 25 reactor-years, respectively, to process 50 tons of weapons plutonium.

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Thus, relatively few physical modifications would be required to handle substantial quantities of plutonium in CANDU reactors.

Simplified Fuel Fabrication: CANDU fuel is produced in smaller and simpler units than those typical of LWRs, potentially reducing the fabrication cost, which is a substantial fraction of the total cost of MOX use.

No Reactor Shutdown Required for Spiking: CANDU reactors are designed to be refueled without being shut down. Thus, although the spiking approach would still require added capital expenditures for a larger fuel fabrication facility, it would not decrease revenue as a result of reactor downtime for refueling.

The CANDU option also has important disadvantages:

Uncertain Canadian Acceptance: The use of existing CANDUs would have to be approved by the Canadian government, the reactor operators (primarily the Ontario Hydro utility), and the relevant regulators (the Atomic Energy Control Board). Atomic Energy of Canada, Limited (AECL), the government-owned designer of the CANDU systems, appears to support this concept, and the Canadian government has reportedly suggested to U.S. representatives that the two countries form an expert group to explore the idea. But further discussions between the U.S. and Canadian governments would be required before it could be determined whether this approach had enough political support to be a practical option. Canada has previously avoided using either enriched uranium or plutonium fuels in CANDU reactors and might reject this plutonium use option as well. Yet Canada has also traditionally played an active role in disarmament; playing a central role in disposition of materials resulting from nuclear arms reductions might well be appealing enough to overcome the resistance to use of weapons materials. Canadian public acceptance is also an open question.

Large-Scale International Plutonium Transport: The distances over which plutonium would have to be transported to be burned in CANDU reactors would be significantly greater than those in using U.S. or Russian LWRs for disposition of those countries' plutonium, even if all the CANDU reactors involved were at a single site. The attendant controversies and risks of theft would be correspondingly greater. Possibly more important in political terms than sheer distances is the need for the material to be shipped across international borders, to a non-nuclear-weapon state.

Lower Radioactivity and Smaller Isotopic Changes: Because of the relatively short burnups that can be achieved with current fuel designs in CANDU reactors (even if the fuel were enriched with plutonium), the resulting spent fuel would be somewhat less radioactive than spent fuel from an LWR, and the isotopic composition of the plutonium in it would remain closer to that of weapons plutonium.

Safeguards Issues of On-Line Refueling: Fuel can be removed from CANDU reactors at any time without shutting down the reactor, and the fuel

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elements are substantially smaller and more portable than is the case for LWRs. Therefore, CANDUs require more intensive safeguarding than do LWRs. For fuel containing more plutonium, still more intensive safeguarding would be needed. Both CANDU reactors and the fresh MOX fuel in store at either an LWR or a CANDU require continuous safeguarding in any case, however. Moreover, the task of accounting for and securing complete fuel assemblies for either a CANDU or an LWR is substantially easier than that of accounting for bulk plutonium at a MOX fabrication plant. Therefore, the *net additional* security risks of using CANDU reactors for this mission compared to using LWRs would be relatively small.

Fuel Fabrication. Like the United States, Canada has no MOX fuel fabrication capacity. Fabricating MOX fuel for CANDUs at the Hanford FMEF facility would be the most expeditious approach, with the same caveats as in the LWR case. The fabrication capacity needed to process 50 tons of excess weapons plutonium in a 25-year campaign in a single reactor using fuel containing 4.6 percent plutonium (the maximum that the manufacturer believes can be used without substantial changes to the reactors) would be 44 metric tons of heavy metal per year, which is within the capability envisioned for FMEF. Spiking all the material in a few years before burning it to spent fuel would require a fuel fabrication capacity substantially larger than that provided by FMEF.

Approvals and Licenses. Gaining approval of the various Canadian institutions and the Canadian public would be a major hurdle for the CANDU option. Licensing reactor operations with plutonium would probably be a less difficult issue than securing agreement on the basic approach. Licensing procedures and standards for plutonium use in Canada are different from those used by the U.S. Nuclear Regulatory Commission.

Safeguards and Recoverability. The safeguards concerns regarding fuel fabrication are similar for LWRs and CANDUs. Because of the need to transport plutonium over longer distances, transport risks would be somewhat greater for CANDUs, and because of the reactor's on-line refueling capability and the portability of the fuel elements, the risks of theft or diversion of fabricated fuel from the reactor could be somewhat greater as well. Both of these risks could be reduced to very low levels with the application of sufficient resources.

Indirect Impact on Civilian Fuel Cycle Risks. The political impact of this approach would be more complex than in the U.S. LWR case. On the one hand, by providing excess plutonium free of charge to another nation, the United States would be demonstrating that it saw no economic value in the material and was encouraging its use in reactors only as an arms control measure. On the other hand, the United States would still be encouraging use of plutonium

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in reactors on a scale wider than would otherwise be the case in a nonnuclear-weapon state.

Cost. The cost of this option is difficult to estimate since no one has yet attempted to fabricate MOX fuel for CANDU reactors on any significant scale. On the one hand, an argument can be made that the subsidy required would be less than in the LWR MOX case, because (1) the fuel is simpler and probably cheaper to fabricate; and (2) the MOX fuel would have a higher energy content (and hence a longer fuel life) than the natural uranium fuel that CANDU reactors normally use, so the increased per-kilogram cost of fabricating the MOX fuel would be compensated, in whole or in part, by the reduced amount of fuel to be fabricated. On the other hand, the subsidy required might also be higher than in the LWR case because the amount of natural uranium CANDU fuel that each kilogram of MOX would substitute for (whose cost would be subtracted from the MOX cost in calculating the subsidy required) would be more than $1,000 cheaper than the LEU LWR fuel that a kilogram of MOX could substitute for.[22] Further study would be required to clarify these cost issues.

Environment, Safety, and Health. Use of plutonium in CANDU reactors raises the same general concerns as those described for LWRs.

Summary. Processing weapons plutonium to spent fuel in existing CANDU reactors appears technically feasible. Canadian approval would be required and is uncertain. Once agreement on the basic approach had been reached, providing fuel fabrication capability and acquiring the necessary approvals and licenses would probably take the better part of a decade, as with LWRs. No insurmountable safeguards or ES&H obstacles are apparent, though the on-line refueling used in CANDU reactors would require intensive safeguarding. The subsidy required to substitute MOX fuel for uranium is uncertain and could be either less or more than in the LWR case.

Advantages: Technically feasible; moderate cost; moderate timing; meets the spent fuel standard.

Disadvantages: Uncertainty of Canadian acceptance; potential safeguards and security issues resulting from required international transport and on-line refueling of CANDU reactors; possible impact on other countries' civilian plutonium programs contrary to existing U.S. plutonium fuel policies.

Conclusion: Using plutonium as MOX in existing CANDU reactors is a leading contender for long-term plutonium disposition.

[22] Whatever might be achieved by using a fuel enriched in plutonium, it is likely that an even better economic result could be achieved by using enriched uranium fuels, which would not involve the extra handling costs of plutonium. But at the outset of its reactor program, the Canadian government made a political decision not to pursue reactor fuel cycles involving technologies, such as enrichment, that could be used to make weapons-grade materials. The use of MOX fuels could be perceived as contravening that policy. Thus, the subsidy for use of plutonium in the case of CANDUs arises in comparison to a fuel cycle that is currently less than optimally efficient, given current fuel prices.

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Major Outstanding Issues: Major technical issues outstanding for CANDU reactors are largely identical to those described above for U.S. LWRs.

The institutional questions are also similar to those relating to U.S. LWRs, except for the questions of Canadian agreement to this option, including the specific international arrangements for shipping weapons plutonium to Canada. The different Canadian regulatory environment requires further examination.

SUBSTITUTION FOR CIVILIAN PLUTONIUM IN EUROPE AND JAPAN

Under established civilian plutonium fuel programs, commercial reactors in Europe and Japan are scheduled to process more than 100 tons of civilian plutonium over the next decade. Plutonium storage and transport arrangements, fuel fabrication capabilities, and reactors licensed to handle plutonium for this task already exist or are planned.[23] One possibility for long-term disposition of excess weapons plutonium, therefore, is to substitute this weapons material for civilian plutonium. Pits would be processed to plutonium oxide in their country of origin, and the resulting oxide shipped to Europe or Japan for fabrication and use.[24] That initial processing and shipment step would be the only aspect of plutonium handling beyond that already planned—with the important caveat that all these facilities would now be using weapons-grade, rather than reactor-grade, plutonium. From the point of view of civilian nuclear energy production, the weapons plutonium would be less radioactive (and therefore easier to fabricate) and have slightly higher energy content than the reactor-grade material it would replace, but would change the physics of the reactor somewhat, possibly requiring some modest adjustments.

What would happen to the displaced civilian plutonium? Three main possibilities exist: one is to expand MOX operations in these countries, involving more reactors and fabrication facilities than those currently planned, so as to process *both* the civilian and the excess weapons plutonium. The advantages of this approach over using the plutonium in the country from whose weapons it came do not appear compelling, since similar fabrication facilities and reactors would have to be licensed and built.

Another possibility is to continue reprocessing and MOX use as planned, and to store the separated reactor-grade plutonium displaced by the weapons plutonium. The net result would be to convert an excess stock of separated

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[23] As of 1993, eight LWRs in France, seven in Germany, and two in Switzerland were using MOX fuel, and more were licensed to do so. Belgium and Japan plan to begin loading MOX fuel in commercial reactors later in the decade.

[24] Alternatively, rather than making use of both the reactors and the MOX fabrication capabilities existing or planned in Europe and Japan, one might make use of only the MOX fabrication capabilities, shipping the resulting fuel back to the country of origin. In that case, however, another round of international shipments of plutonium would be required; and since these existing and planned MOX fabrication facilities will have a hard time handling all the projected civilian plutonium, adding weapons plutonium would mean that separated civil plutonium would build up. Some of the reactors in Europe and Japan currently scheduled to use plutonium fuels would not receive the products of these fabrication facilities as expected and would have to switch back to uranium fuels.

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weapons-grade plutonium to an excess stock of separated reactor-grade plutonium of roughly equal size—a step the committee concludes to be of too limited benefit to justify the complications of the required international agreements and the risks of the required international transport.

The third possibility is to defer reprocessing until existing excess stocks of separated plutonium (both weapons-grade and reactor-grade) are consumed. Reprocessing plants would be kept in cold standby until then.[25] This would require complex international agreements altering a web of existing contracts and spent fuel management policies. Nevertheless, this approach appears considerably more promising, since it could consume both the projected surplus of weapons plutonium and the projected surplus of separated civilian plutonium, without necessarily undermining long-term plutonium fuel cycle plans in any fundamental way.[26]

If the necessary agreements could be reached expeditiously, this would be by far the most rapid reactor option, since the pacing steps of building new fabrication capacity and licensing the various facilities would be avoided; as noted, more than 100 tons of plutonium are expected to be processed in this way over the next decade in any case, so it would be *technically* possible to process the entire stock of U.S. and Russian excess weapons plutonium during that period. Reaching the necessary agreements could involve extended and unpredictable delays, however.

Approvals and Licenses. Gaining agreement to alter the international arrangements and contracts that currently govern reprocessing and plutonium fuel programs would take considerable effort. France and Britain share much of the world market for commercial reprocessing and have just completed multibillion-dollar investments in new facilities. Any proposal to defer reprocessing for an extended period would be seen as a threat to these businesses. Even substantial financial compensation might not be sufficient to overcome such objections. A multinational negotiation would be required in a forum not yet defined.

If some relevant countries were interested in pursuing this option but others were not, the substitution of weapons plutonium for civilian separated plutonium might be only partial. Britain, for example, might agree to defer operation of its Thermal Oxide Reprocessing Plant (THORP) and fulfill its contracts

[25] An important part of this problem is that a substantial amount of the plutonium slated to be used as fuel in civilian reactors over the next decade has already been separated—some 60 tons in Europe and Japan as of the end of 1992. Thus, decisions would have to be made as to whether the weapons stock (which poses a somewhat greater proliferation risk) or the civilian stock (which will build up radioactivity more quickly in storage, requiring further processing if storage is prolonged) should be used first.

[26] The Natural Resources Defense Council, which first suggested this substitution approach, has also argued for an agreement to permanently shut down civilian reprocessing. Such a permanent shutdown, however, is by no means essential to the basic concept, and even if agreement on such a far-reaching step could be reached, doing so would almost certainly be time-consuming, delaying implementation of the option. It is also possible that the parties involved in existing reprocessing contracts might themselves agree, during the period of deferral, to terminate these contracts rather than merely delaying them, with appropriate financial compensation.

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with weapons plutonium instead, even if France continued with its reprocessing operations as planned. By the time such measures could be seriously considered, however, it is likely that THORP will already be operating.

If reprocessing were deferred for an extended period, more spent fuel storage would be required. From the point of view of utility owners of nuclear reactors in countries such as Germany and Japan, the opportunity to ship their spent fuel elsewhere—"out of sight, out of mind"—is one of the primary advantages of reprocessing, and they might be very reluctant to agree (and might be legally constrained not to agree) to an additional decade's worth of spent fuel simply building up at their reactor sites. It is an open question whether the public in France and Britain would accept the alternative of highly radioactive spent fuel continuing to be shipped from abroad to reprocessing sites in their countries for storage, with no reprocessing planned for years to come.

It is also uncertain whether the Russian government would accept this approach since, like the HEU deal (which has raised some controversy in Russia), it would involve shipping large quantities of a key strategic material abroad. Again, financial compensation—provided as a security subsidy by the international community—would probably be required.

The international controversy provoked by the recent shipment of 1.7 tons of reactor-grade plutonium oxide from France to Japan suggests the political difficulties faced by the much larger shipments required for the plutonium disposition mission. To displace civilian plutonium to be used in Europe with Russian excess weapons plutonium, however, only overland transportation would be required. Overland plutonium shipments in Europe are common and relatively noncontroversial, and the association with arms reduction should also help reduce public criticism.

In addition, shipment of large quantities of weapons-grade plutonium, rather than merely reactor-grade plutonium, to non-nuclear-weapon states such as Japan and Germany would almost certainly arouse controversy in those countries and in neighboring states.

Safeguards and Security. Since the weapons plutonium would displace separated plutonium operations that would take place in any case, the *net additional* safeguards issues involved in this option are less substantial than those in other cases. The net additional risks would come from the pit processing required for all options; the large-scale international shipment of plutonium, central to this option; and the difference in proliferation risk involved in the shift from reactor-grade to weapons-grade plutonium.

The risks involved in the large-scale international transport of plutonium required in this option are difficult to judge and depend on the resources applied to reducing them. Once the weapons plutonium arrived in Europe, the risks of diversion or theft during processing and use would be substantially lower than if the material were used in Russia, given the greater social and economic turmoil now taking place there. The need for an agreed, international

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approach to safeguards and security is even more obvious here than it is in other cases.

Indirect Impact on Civilian Fuel Cycle Risks. This "substitution" option sends a variety of signals. Parties interested in maintaining the momentum of commercial reprocessing might view the approach as a fundamental threat to the plutonium fuel cycle (particularly if the option of shutting down civilian reprocessing entirely is considered). Critics of the use of separated plutonium fuels might see an approach that tied disposition of weapons plutonium to continued large-scale MOX operations as irrevocably confirming MOX plans that might otherwise be canceled, and as conferring the political legitimacy of disarmament on MOX operations.

Cost. In this option, a variety of parties would probably demand financial compensation for the materials used or the disruption of previous plans. Russia would probably insist on financial compensation for plutonium used abroad in this way, making it effectively a plutonium purchase arrangement similar to the HEU deal. The reprocessors whose contracts would be delayed or canceled would probably also require compensation, perhaps by means of continued payments on the existing contracts (since those who were to receive plutonium would still be receiving plutonium without reprocessing). Delaying reprocessing of a decade's worth of spent fuel would require additional spent fuel storage at either reactor or reprocessing sites. All told, the subsidy required to financially compensate all the relevant parties might be comparable to the subsidy required to burn plutonium in LWRs that would otherwise burn LEU, discussed above.[27]

ES&H. As with safeguards and security, the net additional ES&H burden would probably be smaller than that for other options, since the weapons plutonium would displace commercial plutonium that would be used in any case. As with other options, there would be some ES&H risks involved in the processing of the pits to oxide, and steps to minimize the risks of accidents during the international shipment would be required. But there might also be some ES&H benefits: workers at MOX fabrication facilities, for example, would be exposed to lower radiation doses from weapons plutonium than they would have been from reactor-grade plutonium, and adding a decade or more to the time spent fuel would be stored prior to reprocessing would reduce the radioactivity of the fuel when it was eventually processed.

[27] Under a financing scheme put forward by the Natural Resources Defense Council, money from MOX-burning electric utilities that would have been paid, under existing reprocessing contracts, for reprocessed civilian plutonium would instead be divided between (1) paying a fair rate of return to the investors in commercial reprocessing plants that would not be operated and (2) paying Russia for its weapons plutonium. The option, in this concept, would not require subsidies beyond those already being paid for reprocessing and MOX use. Additional subsidies would probably be required, however, for purposes such as compensating the reprocessing workers who would be laid off, setting up the required international arrangements for management and transport, additional spent fuel storage, and the like.

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Summary. Substituting excess weapons plutonium for reactor-grade plutonium in existing civilian plutonium fuel programs, with an associated delay in production of additional separated civil plutonium, would be the quickest practical means of disposition for excess weapons plutonium *if* the complex international agreements required could be achieved, but that is very much an open question. More than 100 tons of weapons plutonium could in principle be processed in this way over the next decade, and over a longer period the accumulated excess of civilian plutonium could be consumed as well. The large-scale international transport of separated weapons-grade plutonium required in this option would be controversial and would raise risks of theft. The subsidy required to compensate the various parties is difficult to estimate, but might be comparable to the other LWR options.

Advantages: Potentially quick; moderate cost; meets the spent fuel standard; does not lead to significant net expansion in global handling of separated plutonium; could potentially eliminate both the excess weapons plutonium and the projected excess civilian plutonium.

Disadvantages: Complex international agreements required; reaching necessary agreements could involve major delays; large-scale international plutonium shipments required; could reinforce programs for the use of separated plutonium that might otherwise be canceled or scaled back.

Conclusion: Substituting weapons plutonium for civilian plutonium in planned plutonium fuel programs, with an associated delay in production of additional separated civilian plutonium, is a possibility for long-term plutonium disposition, but is less attractive than the reactor alternatives previously discussed.

Major Outstanding Issues: In this case, the only technical issues are those in the initial stages (including processing pits to oxide and providing adequate security for the international plutonium transport) and some relatively minor reactor and fuel fabrication issues related to the shift from reactor-grade to weapons-grade plutonium.

The institutional issues include:

- the acceptability of the option to the various parties, including those in Russia, the United States, France, Britain, Germany, and Japan, among others;
- the specifics of arrangements for deferral of reprocessing and increases in spent fuel storage;
- the specifics of the international arrangements for the large-scale transportation of plutonium required, and means to address public acceptance of such transport;
- arrangements for safeguards and security throughout the process, including the initial transport;
- financial compensation, both for the parties providing the plutonium and for the parties whose existing plans would be disrupted; and

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Management and Disposition of Excess Weapons Plutonium

- the degree to which such an arrangement might perpetuate programs involving the widespread use of separated plutonium fuels that might otherwise be canceled or scaled back.

OTHER OPTIONS INVOLVING PLUTONIUM TRANSFERS

The CANDU option and the option just described require shipment of weapons plutonium to other countries. A variety of similar options could be envisioned. For example, Russian excess weapons plutonium might be shipped to the United States for disposition there, either in LWRs, by vitrification, or by other means; Russian plutonium might be shipped to Canada for use in CANDUs; or U.S. plutonium, like Russian plutonium, might be shipped to Europe and Japan to substitute for civilian plutonium there.

The use of Russian excess plutonium in U.S. or Canadian reactors would have the advantage that the risks of diversion or theft would probably be lower than they would be if it were fabricated into fuel and used in Russia. The risks of theft involved in the transatlantic shipment could be reduced to low levels if naval forces helped protect the shipment, but the controversies involved would be substantial. The United States would not only have to pay a subsidy for the use of plutonium in reactors, but would probably have to pay Russia for the plutonium as well. In general, this is not likely to be politically attractive in the United States (where it might be seen as shipping a big problem from Russia to the United States) or in Russia (where it might be seen as shipping away a national patrimony). It would seem ironic to ship plutonium from a nation that viewed it as a valuable asset to one that did not. Because the purchase in this case would be strictly bilateral rather than multilateral, however, it might be negotiated more quickly than the substitution for civilian plutonium described above; the basic arrangements would closely parallel the nearly complete HEU deal. The CANDU option would be comparably attractive if Canada were interested in pursuing it. In the most likely approach, the plutonium would be purchased from Russia by the United States, fabricated into fuel in the United States, and would only then be transferred to Canada.

The committee rejects the reverse operation—shipping U.S. weapons plutonium to Russia for use in its reactors. The security and safeguards problem would be increased, the reactors that would use the material would be less safe, and many in the United States would argue that shipping more plutonium to Russia would give Russia a greater potential breakout capability should the government there change in the future.

The option of incorporating U.S. weapons plutonium in a substitution for civilian plutonium in existing plutonium fuel programs in Europe and Japan, however, should be kept open, though all the caveats described above would apply. The primary additional liabilities of this approach (compared to using only the Russian excess weapons plutonium in this way) would be that transatlantic shipment would be required, and that the delay and disruption imposed

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on existing plutonium programs in Europe would be greater. As with the use of Russian plutonium, this would involve shipping weapons-grade plutonium to a number of non-nuclear-weapon states whose plutonium programs are already arousing concern. Moreover, there would not be the motivation, present in the Russian case, of removing the material from an area of current economic and political instability that increases the risks of theft.

EXISTING FAST REACTORS FOR THE SPENT FUEL OPTION

Experimental and prototype liquid-metal reactors (LMRs) exist in a few countries. LMRs (also known as "fast" reactors because of the greater energy of the neutrons in their reactor cores) were originally designed to "breed" more plutonium than they consume. Today, however, their potential role in consuming plutonium and other long-lived actinides and fission products as part of a waste management approach known as "actinide recycle" is also being explored. These reactors have generally been designed to test concepts for repeated reprocessing and reuse of plutonium, an approach applicable to the elimination option (discussed below) but not to the spent fuel option. However, if operated without reprocessing, on a once-through cycle, existing fast reactors offer some near-term capacity for transforming weapons plutonium into spent fuel, particularly as many of them have been designed to use plutonium fuel. If operated as "breeders" as originally designed, these reactors would produce more plutonium than would be fissioned (also true in the case of LWRs with one-third MOX cores), but this plutonium would be embedded in the highly radioactive spent fuel and "blanket" material from the reactor.

Of the few existing LMRs, however, even fewer are now in operation, and some face substantial technical or safety problems:

- In the United States, the experimental breeder reactor (EBR-II) has far too little capacity to play a significant role. The Fast Flux Test Facility (FFTF) reactor, currently on standby and requiring 18 months or more to begin operations, has sufficient capacity to carry out the initial spiking mission (requiring perhaps 25 years to process 50 tons of plutonium), but its life would then be largely consumed, and some additional facility would be required to carry out the spent fuel option. Moreover, this facility produces no electricity and thus no revenue. Hence the committee rejects this approach.
- In the former Soviet Union, there are two operating fast reactors of significant size, the BN-350 in Kazakhstan and the BN-600 in Russia. In principle, these reactors have sufficient capacity to transform roughly 1 ton of plutonium per year into spent fuel. There are questions about these reactors' safety (particularly in the case of the older BN-350), and they certainly cannot operate long enough for disposition of 50 tons of plutonium. Moreover, the cores of these reactors were designed for uranium fuel, and although some tests of a few plutonium fuel assemblies have been carried out in these facilities (including some with weapons-grade plutonium), MINATOM officials report that "a

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complete conversion of these reactors to MOX fuel is not possible owing to their design and physical features."[28] Russian concepts for construction of larger BN-800 reactors are discussed in the next section.

- In France, there are two fast reactors, the experimental-scale Phenix (233 MWe) and the commercial-scale Superphenix (1,200 MWe). Both the currently shut down, in part because of unexplained changes in the rate of the nuclear chain reaction in the core of Phenix. Superphenix has operated only intermittently and has now been shut down for so long that it has lost its license, but a relicensing process is under way. If it could operate safely with greater availability than in the past, Superphenix could, by itself, convert 50 tons of excess plutonium to spent fuel in 20 years. However, Superphenix's past record gives little basis for confidence in future performance, and shipping weapons plutonium to this facility does not appear to have any major advantages over the more general substitution approach described above. Britain and Japan also have fast reactors either operational or soon to be, but these are too small (250 and 280 MWe, respectively) to be of significant value for the spent fuel option.

In short, the use of existing fast reactors should not be pursued further as a major option for disposition of excess weapons plutonium.

OTHER EXISTING REACTORS

There are a variety of other existing reactors that might be used to process weapons plutonium. These include, among others, the plutonium production reactors in the United States and Russia, graphite-moderated reactors, gas-cooled reactors, and a variety of research reactors. None of these appear to offer any significant advantages compared to the options described above, and most appear to have major disadvantages in the areas of cost, safety, or capacity.[29] The committee does not believe that any of these other existing reactors merits further consideration for the plutonium disposition mission.

CONSTRUCTION OF EVOLUTIONARY OR ADVANCED REACTORS FOR THE SPENT FUEL OPTION

If licensing and public acceptance issues facing existing reactors prove insurmountable, a plausible but more costly approach would be to build one or more new reactors, probably on a government-owned site. Such new reactors could be of established designs or evolutionary or advanced designs; a variety of different reactor types have been proposed for this mission.[30] Licensing and

[28] See Yu. K. Bibilashvili and F.G. Reshetnikov, "Russia's Nuclear Fuel Cycle: An Industrial Perspective," *IAEA Bulletin*, Vol. 35, no. 3, 1993, and Kudriavtsev, op. cit.

[29] Even Japan's Fugen heavy-water-moderated reactor, which has been using plutonium fuels for years, is not suitable because its capacity (557 MWt, 165 MWe) is far too small for it to play a major part in the disposition of weapons plutonium.

[30] For a general assessment of nuclear power approaches, see National Research Council (op. cit.). For assessments of several advanced reactor concepts for the plutonium disposition mission, see DOE, *Plutonium Disposition Study*, op. cit.; and Omberg and Walter, op. cit.

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acceptance problems may of course be faced by new reactors built on a government site as well, but these may be less than those that might face the use of existing facilities.

Advanced Light-Water Reactors (ALWRs). A number of advanced light-water reactors (ALWRs) are being developed in the United States and overseas, to meet future nuclear power needs. Their goal is to reduce cost and improve safety compared to previous LWR designs. Some are evolutionary approaches conceptually similar to existing designs; others would make a greater departure from existing designs in order to emphasize the concept of passive safety. The System-80+ reactor developed by ABB-Combustion Engineering, a follow-on to the System-80, is designed for a full core of MOX fuel; other designs could be modified to handle full-MOX cores. Some of these designs, including the System-80+, are well along in the process of design review by the Nuclear Regulatory Commission. Although these designs may have significant advantages for power production, they would not process plutonium any faster, per unit of power produced, than existing reactors.

Modular High-Temperature Gas-Cooled Reactor (MHTGRs). The modular high-temperature gas-cooled reactor (MHTGR) is cooled by high-temperature helium and moderated by the graphite blocks that form its core structure. Its fuel consists of tiny pellets of plutonium or highly enriched uranium, less than a millimeter in diameter, coated in several layers of protective material, which are bonded into fuel rods that, in turn, are loaded into the graphite blocks. (In Russian HTGR concepts, the small particles are bonded into tennis-ball-sized spheres of graphite, which can be loaded into and removed from the reactor without shutdown.) The MHTGR has been designed for improved safety for the next generation of nuclear power. It has not yet met commercial acceptance, in part because of high estimated capital costs. In its recent *PlutoniumDisposition Study*, for example, the Department of Energy found that the MHTGR was the least cost-effective of the five reactors studied.[31] It is undergoing NRC design review, but is less far along in that process than the evolutionary ALWRs.

Because of its unique fuel design, the MHTGR can potentially achieve very high burnup, destroying as much as 80 percent of the total initial plutonium on a once-through cycle.[32] The amount of plutonium remaining in the fuel would still be substantial, however, requiring safeguards comparable to those required for other spent fuel. Given the large global inventory of civilian plutonium, the

[31] U.S. DOE, ibid. General Atomics, the maker of the MHTGR, has criticized this conclusion, arguing that a new HTGR concept, using direct-cycle gas turbines, would be more cost-effective, and that the time lines for other reactors used in the study were more optimistic than those used for the MHTGR.

[32] Figures greater than 90 percent that are sometimes quoted refer to fissioning of Pu-239 or its transmutation into other isotopes, rather than destruction of total plutonium.

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security advantage of this high destruction fraction for one small part of the stock would be small.[33]

Using MHTGRs for plutonium disposition would be expected to cost somewhat more and take somewhat longer, given the licensing uncertainties, than the use of ALWRs. To address the cost issue, General Atomics (GA), the MHTGR's developer, has proposed moving from traditional steam-turbine electricity generation to running the turbine directly with the high-temperature helium coolant from the reactor. If successful, this might reduce capital costs and increase efficiency, thereby increasing revenue. This technology, however, requires further development and would introduce an additional set of licensing issues. General Atomics has agreed with MINATOM to pursue joint development of such a gas-turbine high-temperature reactor (GT-HTR), if the U. S. government decides to provide funding for the project.

Advanced Liquid-Metal Reactors (ALMRs). Advanced liquid-metal reactors (ALMRs), follow-ons to existing LMRs, are under development in a number of countries (though the ALMR acronym is sometimes used to refer only to the U.S. program).

Reprocessing and recycling of plutonium is an integral part of the operating concept of these ALMRs. The most significant advance in the U.S. ALMR program, for example, is a pyroprocessing approach intended to significantly reduce the costs, wastes, and proliferation risks of reprocessing. In this integrated reprocessing approach, plutonium is never fully separated in a form that could be used directly in nuclear weapons, thereby reducing safeguards concerns.[34]

Such reprocessing and reuse of plutonium is applicable to the elimination option (described below), but not to the spent fuel option. If operated in a once-through mode, however, ALMRs could be used to transform weapons plutonium into spent fuel. The capital costs of these liquid-metal reactor concepts are generally higher than those of LWRs, however, and they are much less close to being licensed in the United States than are evolutionary ALWRs. These reactors are of greater interest for the elimination option than for the spent fuel option.

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[33] Advocates also point out that the high burnup of the MHTGR leads to an even more degraded isotopic composition than ordinary spent fuel. Although this would create some additional heat and radiation management issues in the design of a nuclear weapon from this plutonium, the relative problems of pre-initiation would not be greatly increased, since in straightforward designs such as those potential proliferators might use, pre-initiation is very likely even with the isotopic composition of ordinary reactor-grade plutonium.

[34] This approach would mitigate concerns regarding theft of plutonium or covert diversion of material under safeguards. Possession of such a facility, however, would still offer a state the technology needed to produce separated plutonium for weapons, should it choose to do so openly. Since the United States and Russia already possess large nuclear arsenals, this is not a special concern in the context of this report. It must be remembered in considering the potential implications of a worldwide breeder economy employing such technologies, however.

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MINATOM'S preferred disposition option is to use both weapons plutonium and separated civilian plutonium in the three to four BN-800 next-generation liquid-metal reactors it hopes to build. Like other ALMR approaches, however, this raises concerns regarding delay, uncertainty, and cost.

Some MINATOM officials continue to predict that the first BN-800 will be operational by 1997, with others following shortly thereafter.[35] Although construction of the first two of these reactors was begun some time ago, it has been halted for several years as a result of lack of funds and disagreements among the various agencies and publics whose approval is required. These factors are likely to delay completion of these facilities for a substantial period. The cost of these reactors is likely to be significantly higher than the cost of LWRs of equivalent capacity, or the cost of other sources of electricity, and in the current economic environment in Russia, such a large-scale subsidy is likely to be difficult for MINATOM to justify. Safety reviews of the BN-800 design may also result in delays. Because of these factors, some top MINATOM officials acknowledge that the first BN-800 is unlikely to be operational for at least 10-15 years.[36] Even this estimate appears optimistic; it is difficult to rely on the availability of these facilities on any set schedule.

Plutonium would be a less costly fuel for these reactors than uranium (in contrast to the LWR case), because of the higher costs for uranium purchases and enrichment for their more enriched fuels. But Russia already has more separated civilian plutonium than needed to operate these reactors: each reactor requires only 2.3 tons of plutonium as startup fuel, and each produces more plutonium than it consumes thereafter. To use both the 25 tons of civilian separated plutonium already in stockpile and the nominal 50 tons of excess military plutonium in these reactors would mean continuing to add more fresh plutonium as spent fuel is removed, rather than allowing the reactors to fuel themselves through reprocessing and recycle of the plutonium they produce. The net result would simply be a much larger quantity of spent fuel awaiting reprocessing in the fuel cycle for these reactors; the only potential cost advantage would arise from deferring payment of the costs of reprocessing for a longer period.

In MINATOM's concept, the plutonium in the BN-800 spent fuel would ultimately be reprocessed and reused. Thus, although the weapons plutonium would initially be embedded in highly radioactive spent fuel (as in other spent fuel options), it would then be separated again. Only a few tons would exist in separated form at any one time, however. The BN-800 as currently conceived does not incorporate the integral reprocessing approach envisioned for future U.S. liquid-metal reactors (described below) and thus raises greater safeguards and security concerns.

In short, compared to the use of VVER-1000 reactors of vitrification (see below), the BN-800 approach would involve higher capital costs, whose financing

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35 Kudriavtsev, op. cit.

36 See Boris Nikipelov, remarks reported in Mark Hibbs, "Waste Disposal Top Priority for Back End, Nikipelov Says," *Nuclear Fuel*, July 19, 1993.

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is uncertain; probable long delays; more uncertain reactor safety; and greater safeguards and security risks. Nor would the weapons plutonium play any essential role in the BN-800 program.

Similarly, some Japanese officials have suggested that an international group fund a special-purpose LMR to be built in Russia to consume excess weapons plutonium. Like other ALMR concepts, this does not appear competitive with existing or evolutionary-design LWRs for transforming excess weapons plutonium into spent fuel.

Summary of Advanced Reactors for the Spent Fuel Option

Advantages: New evolutionary or advanced reactors could meet the spent fuel standard; evolutionary designs at existing government sites might be easier to license and more acceptable to the public than the use of existing reactors for plutonium disposition.

Disadvantages: Longer time and higher cost than for existing reactors; more advanced designs have significant cost and schedule uncertainties.

Conclusion: Construction of new reactors cannot be justified for this mission unless existing reactors are unavailable and alternative disposition options prove unpromising; if new reactors are built for this mission, they should be based on existing or evolutionary LWR designs, rather than advanced concepts.

Disposal Options

BURIAL WITHOUT PROCESSING

In principle, plutonium in pits or other forms, after placement in suitable canisters, could simply be buried in geologic repositories such as Yucca Mountain or the Waste Isolation Pilot Plant (WIPP), assuming these will eventually open. Plutonium buried in this way would be much easier to recover and use than would plutonium in commercial spent fuel. Thus, this approach does not meet the spent fuel standard, and the committee therefore does not believe that this option should be pursued. In addition, such direct disposal approaches would raise difficult licensing questions concerning the acceptability of plutonium forms such as pits for repository disposal.

Advantages: Potentially cheap and quick.

Disadvantages: Poses only modest barrier to recovery; licensing and public acceptance concerns.

Conclusion: Does not merit government support for the plutonium disposition mission.

VITRIFICATION

One possibility for preparing plutonium for disposal is to combine it with other nuclear wastes that are already being prepared for disposal. In several countries, including the United States, radioactive high-level waste (HLW) is to

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be mixed with molten glass in a process known as vitrification, producing highly radioactive glass "logs" that will be stored for an interim period and then buried in geologic repositories. Such vitrification plants are operational in several countries, and the process can be considered technically demonstrated. Excess weapons plutonium could also be vitrified—either with HLW, with other highly radioactive species, or in a glass bearing only the plutonium itself—but this would add some technical uncertainties.

If plutonium were vitrified along with HLW in the vitrification campaigns currently planned, the glass logs produced would be resistant to theft by virtue of their large size and mass (the U.S. logs are to be some 2 meters long weigh 2 tons), their high radioactivity levels, and the need for chemical separation to retrieve the plutonium. In addition, in both the United States and Russia, these logs are to be stored at major sites in the nuclear weapons complex, with accompanying physical security arrangements (which could be increased further if plutonium were added to the logs). Additional barriers to theft eventually would be provided by isolation in a waste repository and, perhaps, intermixing with outwardly similar waste logs that do not contain plutonium (making it very difficult for a potential proliferator attempting to remove logs from the repository for reprocessing to identify the correct ones to remove). The task of extracting the plutonium from the glass logs would be roughly comparable in difficulty to extraction of plutonium from spent fuel bundles, requiring a substantial remotely operated chemical processing capability. Moreover, experience with separating materials from such glass is far less widely disseminated than experience with spent fuel reprocessing. Although the glass logs scheduled to be produced in planned U.S. HLW vitrification campaigns would be significantly less radioactive than fresh spent fuel (comparable instead to 50-year-old spent fuel), the canisters in which they would be emplaced would still emit doses of more than 5,000 rads per hour at the surface. The plutonium in the logs would remain weapons-grade, rather than being isotopically shifted toward reactor-grade as in the case of the reactor options, but as noted in Chapter 1, nuclear explosives can be produced from either reactor-grade or weapons-grade plutonium. Thus, the committee judges that the plutonium in such glass would be approximately as inaccessible for weapons use as plutonium in commercial spent fuel—particularly as in both the United States and Russia, the major vitrification operations are at nuclear weapons complex sites, with all the associated security.

If the plutonium were vitrified without HLW or other highly radioactive species, so that the glass logs could be handled without remote-controlled equipment, the barrier to reuse would be much lower. The task of extracting the plutonium could be modestly complicated by adding various mixes of chemically similar elements (such as rare earths) to the glass, but this approach has not been examined in detail. Whatever the mixture, it would still be substantially easier to process than plutonium in highly radioactive glass requiring remote handling. For states such as Russia or the United States, a chemical

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barrier alone would be insignificant. For others, it is the committee's judgment that most potential proliferators with the technical expertise, personnel, and organization required to produce an operable nuclear weapon from separated plutonium—a substantial technical task in itself—would also be able to extract plutonium chemically from a glass log not spiked with radioactivity. Thus, vitrification without HLW or other radioactive species is not a viable disposition option in itself, though it might be a first step. If the initial step of vitrifying the plutonium separately before later revitrifying it with HLW were an alternative to longer storage of plutonium in pit form, and could be accomplished quickly and for modest additional cost, this might be a useful approach.

Since plutonium has never been vitrified on a substantial scale, more technical uncertainties exist than in the case of the MOX option. The extent of the further engineering work required is delineated in a set of open questions below.

The most straightforward way to vitrify weapons plutonium with radioactive wastes would be to incorporate it in the HLW vitrification campaigns already planned. At DOE's Savannah River Site, a multibillion dollar program to vitrify HLW, centered on the Defense Waste Processing Facility (DWPF), is slated to begin in 1994-1995 and to continue for the next 20 years. Several thousand highly radioactive 2-ton glass logs will be stored on-site for an interim period and eventually buried in a geologic repository. There have been many years of delays and substantial cost overruns in this project, and it is possible that delays and difficulties will continue. Yet it is likely that by the time the approvals and modifications necessary to add plutonium to the process could be completed—probably 8 to 12 years—this system will be operational.[37]

Once a plutonium vitrification campaign began, it could be accomplished relatively rapidly: Savannah River estimates that 50 tons of plutonium could be incorporated into the planned vitrification campaign in eight years, without increasing the amount of glass produced, at a loading of 1.2 percent by weight in the glass. If higher loadings could be achieved (7 percent plutonium has been dissolved in a somewhat different glass form in laboratory-scale experiments), the time could be reduced accordingly. Thus, if the uncertainties are resolved favorably, the total vitrification campaign could probably be accomplished at least as quickly as the MOX option, and possibly significantly faster.

Similarly, plutonium could be vitrified by using the not-yet-constructed Hanford Waste Vitrification Project (HWVP) melter instead of, or in addition to, the DWPF. Since it is not yet built, the HWVP might be easier to adapt to this mission, though its date of availability is highly uncertain. The project is currently on hold pending review of the plans, and it appears likely to be delayed

[37] Although the current DWPF melter is very large, there appear to be some advantages in smaller melters (which may in fact be considered for the second-generation DWPF melter). If it turns out that using small melters would speed the process of plutonium disposition, that option should be pursued.

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for a substantial period.[38] Vitrification facilities are operational or under construction in several other countries and could in principle be used for this mission, but their use would require international agreements and shipments comparable to those described above for the reactor options.

Alternatively, a waste form could be developed specifically for this mission, rather than piggy-backing on planned vitrification campaigns. This would have the advantage that the waste form could be designed specifically for optimum containment of plutonium. To provide a radiological barrier, the waste might incorporate the highly radioactive cesium-137 that is stored in substantial quantities at Hanford or the wastes stored in a hardened (calcine) form at the Idaho National Engineering Laboratory, instead of the liquid HLW currently scheduled for vitrification. In the case of a glass waste form, smaller melters specifically designed for plutonium vitrification could be used to reduce criticality concerns in the melter. Although this approach might simplify the task of vitrifying the plutonium, the total costs would be higher because all the costs of production, handling, and disposal of this waste form (including the potentially substantial costs of providing and operating facilities capable of handling the highly radioactive materials that might be added to it) would have to be charged to the plutonium disposition mission, rather than only the net additional costs of adding plutonium to a previously planned HLW vitrification campaign.

It is extremely unlikely that a U.S. geologic repository will be ready to receive nuclear wastes of any kind before 2015. Consequently vitrified waste logs, with or without plutonium from weapons, will have to be stored in engineered facilities until a geologic repository is ready to receive them; with plutonium in the logs, safeguards would be required. The same is true, of course, for spent fuel from nuclear reactors. All of the planned capacity in the Yucca Mountain repository will be filled by wastes already scheduled to be produced. Therefore production of additional waste products specifically for weapons plutonium disposition (rather than piggy-backing on planned HLW vitrification campaigns) would require either displacing other wastes now scheduled to go into Yucca Mountain, expanding that repository's capacity, or waiting for an indeterminate time until a second repository became available. Again, the same is true for spent fuel, if the reactor used for plutonium disposition would not otherwise have operated and produced this waste.

Approvals and Licenses. Certifying the safety of the additional processes needed to add plutonium to currently scheduled HLW vitrification campaigns would take several years. Careful attention would have to be paid to melter design to ensure against criticality, and to the system for treating gases released

[38] Another HLW vitrification facility is being built at West Valley, New York, but the amount of glass to be produced there is too small to support the full plutonium disposition mission. There seems little point in building plutonium-handling facilities there if either Savannah River or Hanford, both of which have extensive plutonium-processing experience, could accomplish the mission.

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during vitrification (the "offgas"), which must prevent release of plutonium into the environment and accumulation of plutonium within the offgas system itself. These engineering issues, while challenging, appear resolvable. Gaining public acceptance at the relevant sites may be more difficult, but if (1) the public is included in the decision-making process, (2) the association with arms reductions is made clear, and (3) a plausible case can be made that once processed, the plutonium will eventually be shipped elsewhere for burial in a geologic repository, then public approval should be achievable. Overall, licensing and approval for this approach would probably be easier than for MOX, at least in the United States. Siting approval and licensing for a vitrification facility dedicated solely to plutonium disposition would probably be more protracted than for an approach piggy-backing on already scheduled HLW vitrification campaigns.

Certification of the plutonium-bearing glass as a suitable waste form for emplacement in a geological repository would be the highest hurdle. Introducing plutonium into Yucca Mountain would be nothing new: the nominal 50 tons of excess weapons plutonium is small compared to the 600 tons of plutonium in the spent fuel to be placed in the repository. But this plutonium would be in HLW glass, which would not otherwise contain substantial quantities of plutonium, rather than in spent fuel.

The performance of the glass in preventing release of this plutonium, however, is expected to be at least as good as that of the spent fuel, and it appears that the addition of plutonium would not degrade the ability of the glass to contain its other radioactive constituents. A number of studies indicate, moreover, that because of its extremely low solubility plutonium is not a major contributor to potential long-term health risks from the repository in most scenarios. Thus, although containment of the plutonium in the repository and preventing releases to the environment would require careful examination in the process of licensing such waste forms for disposal, these issues should be resolvable.

Criticality of the logs over the very long term remains a concern. The amount of plutonium that can be placed in the glass without it going critical is greatly increased by the presence of boron (which absorbs neutrons), in the borosilicate glass. But the solubility of boron in water is much higher than that of plutonium. Over tens of thousands of years, if the materials in the repository were exposed to water, the boron in the glass could leach away, leaving behind the plutonium and the uranium-235 it produces by radioactive decay. Preliminary calculations suggest that with plutonium loadings in the range of 1-3 percent, the logs would not be capable of sustaining a chain reaction even if all the boron and lithium leached away, unless water also filled a large fraction of the volume of the log. With similar assumptions concerning leaching away of neutron poisons and flooding with water, spent fuel (particularly MOX spent fuel, with its higher plutonium content) would also pose the possibility of criticality in the repository.

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The result, if the waste did go critical, would be a low-power underground reactor, similar to the Oklo natural reactor that operated in Africa more than a billion years ago, which would generate heat in the repository and convert some fraction of the buried plutonium to buried fission products. While the quantity of fission products produced would be substantially smaller than those originally buried in the repository, they would be produced at a time thousands of years in the future, when nearly all of the original fission products would have decayed away and the engineered barriers to prevent their release might have failed. Although such a low-power underground reactor would not necessarily be a threat to public health or safety, this issue could interfere with licensing, and it is prudent to resolve it sooner rather than later.

One promising approach is to add another neutron poison to the glass, whose solubility in the repository environment is comparable to or lower than that of plutonium, such that it can be demonstrated that it will not be leached from the glass more quickly than the plutonium. Some of the rare earths, such as gadolinium, might be candidates. More research on this long-term criticality concern is required, but the committee believes that with methods such as these, the issue can be resolved in a few years at modest cost.

Safeguards, Security, and Recoverability. As noted earlier, the difficulty of extracting plutonium from the glass logs would be generally comparable to the difficulty of extracting plutonium from spent fuel, with respect to both the complexity of the chemical engineering operations involved and the intensity of the radiation fields with which anyone handling the logs would have to cope.

As for the opportunities for diversion or theft of the materials, it is important that all necessary plutonium operations for the vitrification option—both pit processing and production of the plutonium-bearing glass—could be carried out at a single nuclear weapons complex site with extensive safeguards and security. Thus, the number of required transportation and storage steps, and the associated opportunities for theft, would be less than in most of the reactor options.

Fabrication of HLW waste logs would also be easier to safeguard than fabrication of MOX fuel bundles.[39] Monitors would have to confirm only the single step of mixing the plutonium with the HLW. Once that step had taken place, the plutonium would be in an intensely radioactive mix and very difficult to divert. There would be no capability within the vitrification facility for reseparating the plutonium from the HLW. MOX fabrication, by contrast, requires many steps involving large-scale bulk handling of plutonium with inherent accounting uncertainties, and at each step of the process the plutonium remains in a form from which it could be readily reseparated.

For the glass operation, however, once the plutonium had been mixed with the HLW and incorporated in glass, the very high radioactivity and strong neutron absorption of the glass log would make accurate nondestructive assays of

[39] Interview with Thomas Shea, IAEA Safeguards Division, August 1993.

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Management and Disposition of Excess Weapons Plutonium

the amount of plutonium in the glass difficult. Thus, the traditional material accounting approach of detailed measurement of the inputs and outputs of the plant might have to be modified, with safeguards relying more on confirming that the plutonium was mixed with HLW, and on containment, surveillance, and security measures to ensure that no plutonium was removed from the processing area or from the site without authorization. Although this would be an engineering challenge, adequate technologies exist to safeguard the glass production process, particularly given its inherent simplicity compared to the MOX fabrication process.

Once the logs had been produced, they could be stored and safeguarded relatively cheaply until repositories were ready to accept them, in facilities already planned, just as in the case of spent fuel.

Indirect Impact on Civilian Fuel Cycle Risks. Treating pure weapons-grade plutonium as a waste to be disposed of would demonstrate the U.S. policy of generally discouraging the use of separated plutonium reactor fuels.

Cost. A team at the Savannah River Site has estimated that vitrification with HLW would cost some $600 million, plus approximately $400 million to carry out the preliminary steps, including pit processing (which would also be required for the reactor options).[40] The same team puts the cost of vitrification without HLW at less than $200 million (plus the same $400 million pre-processing cost). These estimates are uncertain by at least a factor of two. The cost of a separate plutonium vitrification campaign that incorporated radioactive materials such as cesium-137 would be much higher, because the high costs of processing highly radioactive glass would then have to be borne entirely by the weapons plutonium disposition mission, rather than being shared by HLW disposal operations already planned.

ES&H. The ES&H issues of adding plutonium to planned vitrification campaigns require further study. Because the plutonium is far less radioactive than the HLW, the net additional radioactivity to which workers would be exposed at the melter stage would be negligible. However, potential exposures in earlier processing must be considered, along with the risks of plutonium forming an aerosol that could be inhaled. Potential accident scenarios that could result in criticality or release of plutonium to the environment must be carefully addressed. Although these issues would pose engineering challenges, the state of the art should permit stringent regulatory standards to be met.

Concerns related to the long-term environmental impact of placing plutonium-bearing glass into geologic repositories are described above.

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[40] J.M. McKibben et al, "Vitrification of Excess Plutonium," Westinghouse Savannah River Company, WSRC-RP-93-755, 1993; and additional information provided by McKibben. This is an undiscounted estimate; discounting by 7 percent per year (see Chapter 3) would reduce the billion-dollar figure by roughly half, for comparison to other options. These estimates also include previtrification in a plutonium-only glass; eliminating this step would probably lower costs somewhat.

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Vitrification of Russian Plutonium. It would also be possible to vitrify Russian excess weapons plutonium. A waste vitrification facility with a nominal output of 1 ton of glass per day is in operation at the Chelyabinsk-65 site in Russia and, by September 1993, was reported to have processed 150 million curies of radioactive waste, at a loading of between 150,000 and 200,000 curies per ton. The glass produced has somewhat higher loadings of radioactivity than are planned at Savannah River. Nearly 700 million curies of HLW remain in waste tanks at this site, similar to the holdings at Savannah River and somewhat more than the amount at Hanford.[41] The phosphate-glass composition employed at this facility appears to be both less durable and less resistant to criticality if plutonium is embedded in it than the borosilicate glass planned for U.S. vitrification. Although borosilicate glass forms have been studied in Russia, the committee is not aware of any Russian plans to switch to a borosilicate glass, or of any estimates of the cost and schedule for modifying the Russian facility to produce borosilicate instead of phosphate glasses.

Some of the small melters developed in the U.S. vitrification program, however, are relatively low cost and transportable, and could therefore be shipped to Russia for a vitrification campaign there if modification of existing Russian melters proved too costly. Russia has operational remote-handling facilities that could be used to operate such melters while incorporating HLW or cesium capsules in the product to create a radioactive barrier. Such small melters could be used to produce either small glass logs (which would pose a somewhat lower barrier to theft) or large glass logs like those produced in larger melters. The net cost of this approach depends on whether it is seen as an alternate way of handling the HLW vitrification campaigns already planned (in which case much of the cost might be offset by reductions in other vitrification costs) or as a separate campaign for disposing of weapons plutonium.

In general, Russian authorities have objected to weapons plutonium disposition options that would "throw away" the plutonium without generating electricity. Moreover, given the environmental legacy of past handling of plutonium and the widespread public distrust of government safety assurances, gaining public acceptance and licenses for a plan to bury plutonium in a repository in Russia might be difficult. MINATOM itself has recently emphasized the environmental dangers of burying long-lived actinides such as plutonium, as part of its advocacy of a closed fuel cycle in which plutonium would be reprocessed and reused. The ease of storing and safeguarding the vitrified logs, however, would make it possible for Russia to defer decisions on committing them to geologic disposal for a substantial period, as in the case of spent fuel.

[41] Interview with Donald Bradley, Pacific Northwest Laboratory, October 1993. See also D.J. Bradley, "Radioactive Waste Management in the Former USSR: Volume III," Pacific Northwest Laboratory, PNL-8074, June 1992. For figures on wastes in the U.S. complex, see, for example, U.S. Congress, Office of Technology Assessment, *Long-Lived Legacy:Managing High-Level and Transuranic Waste at the DOE Nuclear WeaponsComplex*, (Washington, D.C.: U.S. Government Printing Office, May 1991).

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Applicability to Other Forms of Plutonium. As noted, vitrification may have an important role to play in dealing with the many tons of plutonium that exist as scrap and residues in both the United States and Russia. Small melters that could be set up on-site to vitrify these scraps and residues—and thereby both stabilize them to reduce the hazards of near-term storage and prepare them for ultimate disposal—deserve consideration.

Summary. Vitrification of excess weapons plutonium with HLW or other highly radioactive materials appears to be a feasible approach to creating a disposal form roughly as inaccessible for use in weapons as plutonium in commercial spent fuel. The technical uncertainties in this approach, however, are greater than for the MOX option. By incorporating plutonium into already planned HLW vitrification campaigns, tens of tons of plutonium could be disposed of in a campaign lasting less than a decade, beginning roughly a decade from now, for a probable cost of the order of $1 billion. Vitrification of Russian plutonium would require overcoming strong Russian government resistance to options that throw away plutonium's energy value and would be somewhat more complicated because of different vitrification approaches currently in place in Russia.

Advantages: Moderate timing; moderate cost; meets the spent fuel standard; can be accomplished at single government-owned nuclear weapons complex site; process easier to safeguard than MOX fabrication.

Disadvantages: Unresolved technical uncertainties; discards energy value of plutonium; may be unacceptable to Russian government for Russian plutonium.

Conclusion: Vitrification is a leading contender for long-term plutonium disposition.

Major Outstanding Issues: Subjects that require further study include:

- the amount of plutonium that can be dissolved in the glass, while maintaining an acceptable waste form for ultimate geologic disposal;
- the required modifications to existing vitrification approaches;
- criticality safety in the melter and safety of the system to treat gases released during vitrification;
- relative advantages of large and small melters for this mission;
- long-term performance of plutonium-bearing glass in a repository environment, including effect of plutonium on glass stability, boron leaching, criticality risks, and the use of neutron poisons in addition to boron to mitigate criticality;
- ES&H and safeguards;
- recoverability of plutonium in HLW glass, compared to spent fuel;
- costs and schedule to incorporate U.S. excess weapons plutonium in the Savannah River vitrification campaign, the Hanford vitrification campaign, or a separate vitrification campaign;

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- costs and schedule to modify the ongoing Russian vitrification campaign to produce borosilicate glass and incorporate plutonium, or of a separate plutonium vitrification campaign; and
- applicability of vitrification options, particularly those using transportable melters, to plutonium in other forms, such as scrap and residues.

A plutonium vitrification campaign would presumably be carried out by the government organizations already working on vitrification. Institutional issues would include:

- safeguards and security for the process, including possible international agreements;
- licensing and local approval for plutonium vitrification operations;
- the likely political impact of plutonium disposition on other countries' plutonium fuel programs; and
- the likelihood of Russian government and Russian public agreement to vitrify Russian excess weapons plutonium.

Deep Boreholes

Very deep boreholes—perhaps 4-kilometers deep—have been considered in several countries for disposal of spent fuel or HLW, and this is a possible approach for plutonium disposal as well. Excess weapons plutonium would generate far less heat than spent fuel or HLW, and would take up much less space, but it could raise greater concerns regarding potential criticality. Because of the boreholes' great depth and the very low permeability of granite, boreholes might isolate such materials from the biosphere for an even longer period than mined geologic repositories could. Nevertheless, deep boreholes have not been selected as the preferred disposal method in any country, in part because of the greater difficulty (compared to mined geologic repositories) of engineering the disposal site, characterizing the physics and chemistry of the surrounding rock, monitoring the material once emplaced, and retrieving it if required. Sweden currently has the most active remaining program examining deep-borehole disposition as a backup to the preferred mined repositories. Boreholes have received far less detailed study than have mined repositories, and therefore a larger number of outstanding technical issues remain.

Boreholes have been drilled in crystalline rock to depths of 1.5 kilometers or more in the United States and four other countries, though the mission of emplacing large quantities of material at depth would pose somewhat different challenges. In current concepts, the material would be placed in canisters in roughly the bottom 2 kilometers of a 4-kilometer-deep hole, with clay seals separating each canister and a long column of clay, topped by concrete, on top of the entire assembly of canisters. Figure 6-3 illustrates this concept. Plutonium might be placed in specially engineered canisters after being processed

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and combined with neutron poisons to reduce criticality risks.[42] Fifty tons of excess plutonium could be placed in one or several holes. Cost estimates for drilling such holes are in the range of $100 million. The process could be accomplished quickly *once thenecessary approvals and licenses had been secured* (a problem discussed below).

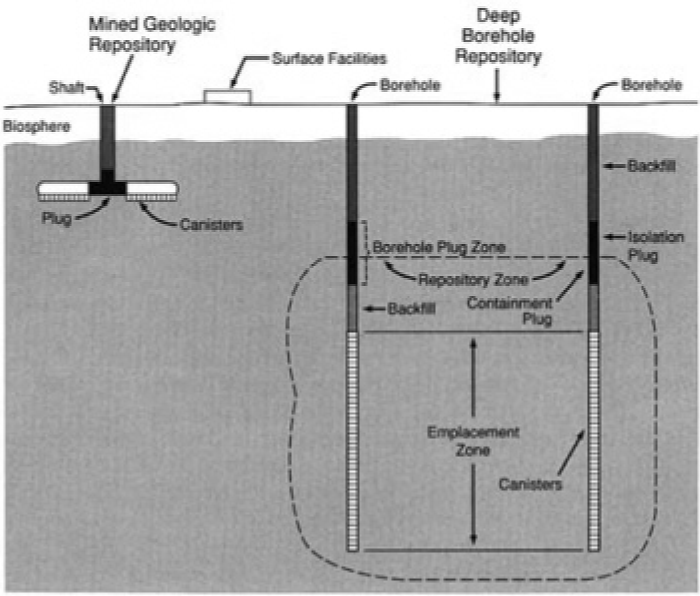

FIGURE 6-3 Deep borehole disposal
Source: Redrawn from Woodward-Clyde Consultants, *Very Deep Hole SystemsEngineering Studies*(San Francisco, Calif.: Woodward-Clyde Consultants, 1981).

The risk of the material being released into the environment from the borehole requires further study. There are substantial reasons to believe, however, that this risk should be low if the borehole is in an area free of geologic activity that might bring the material to the surface, and free of vertical faults in the rock that might create a pathway for the material to migrate toward the surface. In particular, the very saline water that is often found at great depth would make it virtually impossible for material in the borehole to rise toward the surface by convection: this water is significantly denser than the fresher water above and therefore does not rise through it even if heated.

[42] The committee does not believe its role is to suggest drastic changes in current waste management approaches unless they are necessary to solve the plutonium disposition problem. Hence, it would not recommend the borehole approach for disposing of plutonium that had already been vitrified with HLW, or transformed into spent fuel in reactors, unless U.S. policy for disposal of HLW and spent fuel changed to favor the borehole approach. This does not appear likely.

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Plutonium in deep boreholes on the territory of Russia or the United States would be inaccessible to potential proliferators, but would be accessible to the state in control of the borehole site. Redrilling the hole could be accomplished within a few months. Such activity would be observable weeks or months before the plutonium was retrieved, particularly if the site were subject to agreed monitoring (unmanned seismic detectors could sense any drilling activity).

Thus, deep boreholes represent a class of options that go a long way toward eliminating the proliferation risks posed by excess weapons plutonium, but do not go quite as far in reducing the potential breakout risks associated with this material's existence. Given that leading segments of the Russian government see plutonium as a valuable asset that must not be irrevocably thrown away—but also perceive the proliferation risks associated with the material—options such as the borehole approach might be attractive, representing in a sense a form of "storage" of plutonium, greatly reducing near-term security risks while saving the plutonium for the day when it can economically be used as fuel.

Gaining the necessary approvals for such an approach could be problematic. In the United States, a new waste disposal method would have to pass the same hurdles that have raised difficulties for geologic repositories, including: site selection; congressional approval, including funding; regulatory approval; and public acceptance. Deep-borehole disposal faces obstacles on each count. Over the years, Congress has allocated billions of dollars for studies of geologic repositories, and has taken the politically difficult step of selecting a site. Obtaining approval for an entirely new approach would be difficult, as would gaining the necessary funding.

The regulatory agencies have struggled for years to develop a regulatory framework for licensing a mined geologic repository, and they have developed some technical competence for reviewing repository proposals. Deep-borehole disposal, although similar in some respects, would require new regulations and new expertise. Perhaps more importantly, it would require the Nuclear Regulatory Commission (NRC) to develop licensing methods without the ability to monitor or readily retrieve the materials emplaced; initial monitoring and retrievability are a central basis for current NRC repository licensing concepts. Furthermore, the NRC would likely require quantitative values for the parameters that characterize the local geochemistry of the rock, the extent of fracturing of the rock, the details of water flow, and similar factors (as it has for Yucca Mountain). Obtaining comparable data for deep-borehole sites would be a major challenge. Failure analysis, particularly of the disposal process, has yet to be done.

None of these tasks is impossible, but they will take time. Public acceptance is also uncertain: the public would have to be convinced that this approach was acceptable for plutonium disposal, though it was not being pursued for HLW or spent fuel. During the approval period, the plutonium would remain in intermediate storage, with all the associated problems discussed previously.

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In the different and evolving regulatory environment in Russia, where no consensus on repositories or sites has yet been reached, these matters are difficult to judge, although they might present fewer problems than in the United States.

Advantages: Implementation steps are quick and relatively low cost; appears to present low environmental and safety risks; greatly reduces proliferation risk; may be more politically acceptable to Russian government than other disposal options.

Disadvantages: Readily recoverable by host government; requires further development; possibly large costs and delays in licensing a new geologic disposal approach.

Conclusion: At present, because it is less fully developed, the borehole option ranks behind the spent fuel and vitrification options as a contender for long-term plutonium disposition, but further research could show it to be comparably attractive.

Major Outstanding Issues: The borehole option is the least thoroughly studied of the options the committee has identified as deserving further attention. Outstanding technical issues include:

- mechanisms for possible transport of radionuclides to the surface;
- advantages and disadvantages of different geologies and sites for borehole disposal;
- methods of collecting data on the characteristics at depth of potential sites, sufficient to permit analysis necessary for site selection and licensing;
- approaches to monitoring and retrieval of emplaced materials;
- preprocessing required to create an acceptable waste form for disposal and reliably prevent criticality in the borehole;
- techniques for emplacement of the material in the hole;
- potential failure modes, particularly during emplacement, and their possible consequences; and
- costs, including those for site selection, data collection, analysis, licensing support, drilling of the hole, emplacement, and follow-up monitoring.

The primary institutional issues to be addressed in this case relate to licensing, including specific approaches, difficulties, and likely schedules, in both the U.S. and the Russian contexts.

SUB-SEABED DISPOSAL

Disposal of HLW by burial in the mud layer on the deep ocean floor—"sub-seabed disposal"—has long been considered the leading alternative to mined geologic repositories.[43] In recent years, however, with the choice of

[43] This sub-seabed option in mid-ocean areas should not be confused with the idea that wastes should be placed in the "subduction zone," where one tectonic plate is slipping beneath another and the wastes would therefore be carried deep beneath the earth's crust. The problem with this approach is that

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mined geologic repositories as the primary disposition approach, sub-seabed disposal has received little further attention or funding.

This approach could also be used with weapons plutonium. The differences between plutonium and HLW are noted above in the discussion of deep-borehole disposal.

The deep ocean floor in vast mid-ocean areas is remarkably geologically stable; smooth, homogeneous mud has been slowly building up there for millions of years. The concept envisioned for HLW was to embed it in containers perhaps 30 meters deep in this abyssal mud, several kilometers beneath the ocean surface. One approach for doing so would be place the material in long, thin "penetrators"—inert metal shells—that would be dropped from ships and would then penetrate easily into the mud, which, it is believed, would flow to reclose the hole above them (see Figure 6-4.) The penetrator casing could be expected to last for as much as a few thousand years—long enough for the main radioactive components of HLW to decay, but not long enough for plutonium to do so—but the mud itself would be the primary barrier to release of the material into the ocean, because the time required for diffusion of radionuclides through this mud would be very long. Although there are some life forms in the upper meter or so of the mud, sampling studies indicate that the emplacement depths envisioned for this purpose are far below the depths where life forms exist that would be expected to have a major impact on transport of radionuclides to the surface. Moreover, although huge deep-ocean storms that perturb the ocean bottom have been detected in some areas of the ocean, floor samples demonstrate that other areas have been free of such storms for substantial periods of geologic time. The suitable seabed area exceeds the land area available for deep geologic repositories by several orders of magnitude.

If this method were used for excess weapons plutonium, some preprocessing would probably be desirable to limit the risk of criticality, particularly as the plutonium containers would eventually flood with water. The processed material (perhaps a plutonium-boron composite) could be placed directly into the penetrators, which would then be emplaced by ship. The process could be quick, if licensing and public acceptance obstacles could be overcome. Although the committee has not done a full cost analysis, implementation of this option might be in the lower range of costs, probably amounting to several hundred million dollars for the nominal 50 tons of excess weapons plutonium. As with the borehole approach, however, the costs of developing and licensing the option would be far higher than the costs of implementation.

The recoverability of plutonium placed in penetrators in the sub-seabed mud would depend on several factors. If the plutonium remained confined in the penetrators and if the location where they were embedded was

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even "fast" seafloor motions proceed at a rate of the order of 1 centimeter per year, meaning that in all of historic time (some 5,000 years) the material would only have moved 50 meters. Furthermore, the subduction zones are geologically active and unpredictable—prone to volcanoes, among other phenomena. For these reasons the committee did not consider the subduction-zone option any further.

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Management and Disposition of Excess Weapons Plutonium

approximately known, countries with sophisticated deep-ocean technology could recover the plutonium, albeit at some cost. Sonar could detect the solid penetrators in the mud. Once detected, the penetrators could be retrieved by ocean drilling ships, or by ordinary ships equipped with a small derrick that could be lowered to the bottom for canister retrieval. Clearly, knowledge of the precise location (which would be available to the country that emplaced the penetrators) would make the job easier. For less developed countries and subnational groups, recovering plutonium from the seabed might be more costly and time-consuming than recovering plutonium from spent fuel.

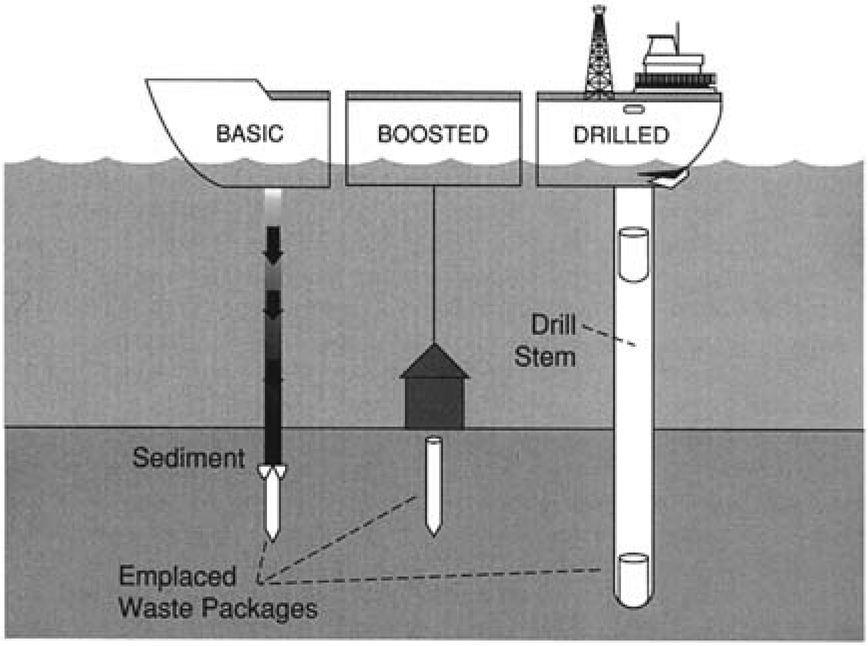

FIGURE 6-4 Sub-seabed disposal
Source: Redrawn from JK Associates, *The Subseabed Disposal Project:Briefing Book 1985* (JK Associates: 1985).

To limit such recovery possibilities, the area in which the plutonium-bearing canisters had been deposited could be monitored for an indefinite time, if that were agreed on. In addition, recovery could be made more difficult by the use of "stealth" canisters designed to be difficult to detect with sonar, or by eliminating the detectable penetrators sooner rather than later, for example, by using canisters designed to dissolve soon after emplacement or using drills that would pump a plutonium solution directly into the mud, at appropriate depth, without the use of a canister. Such concepts have not been considered for the disposal of HLW, where retrieval is not an issue and the canister provides a

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major barrier to release of the radioactive materials, most of which decay far more rapidly than plutonium.

Sub-seabed disposal would face intense political opposition from many quarters, and a complex web of national and international legal hurdles and regulations. The U.S. Marine Protection, Research, and Sanctuaries Act, also known as the Ocean Dumping Act, forbids all dumping of high-level radioactive waste at sea and has been interpreted as including sub-seabed disposal. In addition, the London Dumping Convention of 1972 bans "ocean dumping" of high-level radioactive waste. The parties to the convention have never agreed on whether it prohibits emplacement of wastes beneath the ocean floor, but a majority of the parties have expressed that view in the past. The parties have agreed that if the technical feasibility of the concept is demonstrated and one or more countries wished to pursue such a disposal approach, the convention would be the appropriate forum in which to consider the matter.

On November 12, 1993, the United States and 36 other nations voted to extend the convention to ban dumping of low-level radioactive waste as well. Proposals for an explicit prohibition on sub-seabed disposal are reportedly slated to be discussed in 1994 or 1995. Further, the Law of the Sea Treaty, if it enters into force, would create an international authority that would regulate activities on the seabed, which would presumably assert authority over sub-seabed disposal.

In addition to this legal framework, any proposal for disposal in or below the oceans is likely to provoke intense public and political opposition, both within the United States and internationally. In short, gaining approval from a majority of the parties to the London Dumping Convention for sub-seabed disposal of plutonium, and overcoming the political, legal, and regulatory hurdles (including providing experimental data that do not yet exist), would be difficult, uncertain of success, time-consuming, and expensive. Given the strong resistance of many countries to placing such wastes anywhere in or below the ocean, the committee does not believe that such an approach should be pursued if it is merely to address excess weapons plutonium—a problem that only two countries (the United States and Russia) are faced with, and for which other options are available. Only if the sub-seabed option were reopened for other purposes would this avenue be worth considering in more detail.

Advantages: Technical implementation potentially quick and moderate to low cost; makes recovery of the plutonium by likely proliferators difficult.

Disadvantages: Recoverability by emplacing state; direct conflict with international agreements; public acceptability and licensing difficulties, which could mean substantial delays and costs.

Conclusion: Options to reduce retrievability are worthy of some further study, but not a leading contender.

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UNDERGROUND NUCLEAR EXPLOSIONS

The Russian company CHETEK, associated with the Arzamas-16 nuclear weapons laboratory, has proposed that plutonium be disposed of with underground nuclear explosions. Hundreds or thousands of pits would be arranged around one or more nuclear devices at an existing underground nuclear test site.[44] The detonation would vaporize both the pits and tons of rock surrounding the blast, instantly incorporating the plutonium in a glassy matrix of vaporized and rehardened rock.

This method is potentially quick and of moderate cost: depending on the number of pits destroyed in each blast, the number of explosions required might be in the range of a few to a few dozen, implying a cost of hundreds of millions to a few billion dollars.

This method results in embedding tens of tons of plutonium in a completely nonengineered and inherently somewhat unpredictable waste form, in an underground location not selected for or designed as a long-term repository, thus raising severe environmental concerns. In particular, concerns over potential long-term criticality of the underground plutonium, after possible differential leaching of different constituents in the rock, would be far more difficult to address than in the case of the vitrification or spent fuel options, since there would be no opportunity to engineer the resulting waste form with this problem in mind. The amount of plutonium coming from tens of thousands of weapons would be an order of magnitude more than has already been deposited at these sites in the course of past nuclear testing. Moreover, this approach would conflict directly with the current U.S. and Russian policy of extending the current nuclear testing moratorium and pursuing a comprehensive ban on nuclear testing. This option would also face major problems of public and institutional acceptance.

Finally, the material would be recoverable by the state that emplaced it, providing a plutonium mine with substantially more plutonium in each ton of rock than there is gold in some mines that are profitably mined today, and with dramatically lower near-term radiological hazard than is the case for the spent fuel or vitrification options.

Advantages: Potentially quick and moderate cost; makes recovery of the plutonium by potential proliferators difficult.

Disadvantages: Substantial environmental concerns; directly conflicts with current nuclear testing policy; remains recoverable by emplacing state; doubtful public acceptability and licensing.

Conclusion: Does not merit government support for the plutonium disposition mission.

[44] In principle, if nuclear safety issues could be adequately resolved, nuclear weapons themselves could be destroyed in this way, without requiring disassembly. Although this might significantly speed the overall disarmament process, it would mean throwing away the valuable materials in the warhead, such as highly enriched uranium, as well as those that have little value. In any case, the overall approach has so many liabilities that this variant is not of great interest.

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ENCAPSULATION WITH SPENT FUEL BUNDLES OR HIGH-LEVEL WASTE LOGS

Several variants of the direct burial option have been proposed in which excess weapons plutonium might be hidden among the highly radioactive materials that will be buried in deep geologic repositories. For example, spent fuel bundles will be placed in large casks for repository disposal: the excess weapons plutonium could be formed into fuel bundles of identical shape and appearance, and placed inside casks containing other genuine spent fuel bundles. It would be effectively impossible to identify the casks that contained such "mock" fuel bundles from the outside, and it would be difficult for potential proliferators, even if they could get into the repository and find one of the appropriate casks, to open it safely with equipment that could plausibly be brought into the repository. Removing casks from the repository for later opening would be possible in principle, but difficult and easily detectable. A similar idea is to place canisters containing critically safe arrangements of some plutonium-bearing material, such as plutonium oxide or a plutonium-bearing glass without fission products, into casks containing spent fuel or HLW glass logs.

Compared to vitrification with HLW, these approaches seek to make the plutonium nearly equally inaccessible to potential proliferators, while leaving it in forms that would be recoverable by the emplacing state. As discussed in the case of the deep-borehole option, such recoverability means that these approaches would do less to reduce breakout risks or potential negative impacts on the arms reduction and nonproliferation regimes than would other approaches. Recoverability could increase the prospects of political acceptance by the Russian government, however.

These approaches cannot be implemented until geologic repositories are available. In the United States, this will not occur until after 2010; in Russia, the effort to develop an underground repository is in its early stages. In both countries, the possibility that a permanent repository would not be available for many decades cannot be excluded. In addition, if these techniques were used for permanent disposal rather than intermediate storage, the forms in which the plutonium was placed into the repository would have to be analyzed as to criticality risks and licensed as acceptable waste forms for disposal. Even more than in the case of the vitrification option discussed above (where the form in which the plutonium would be placed has been designed and studied for years as a repository waste form), this is problematic and could involve significant delays and costs.

Advantages: Technical implementation quick and low cost; makes plutonium largely inaccessible to potential proliferators; may be more politically acceptable to Russian government than other disposal options.

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Disadvantages: Easily recoverable by host government; new geologic disposal waste forms could raise environmental issues and licensing delays; cannot be implemented until repositories become available.

Conclusion: Does not merit government support for the plutonium disposition mission.

Beyond the Spent Fuel Standard

Although the spent fuel standard is an appropriate goal for excess weapons plutonium disposition, further steps should be taken to reduce the proliferation risks posed by *all* of the world's plutonium stocks, including plutonium in spent fuel. Separated reactor-grade plutonium poses risks less than, but comparable to, those of separated weapons-grade plutonium. Spent fuel poses proliferation risks that are initially far lower, but increase with time as the intense radioactivity that provides the most important barrier to recovery of this material decays. It is time for the governments of the world to turn their attention to this problem again, to examine how nuclear power can best be managed to minimize these risks. That broad question is beyond the charge of this study and will be affected by many economic, technical, and political factors outside its purview—many of which have changed since the last major international review (the International Nuclear Fuel Cycle Evaluation, or INFCE) and are difficult to predict.

Nevertheless, a few remarks are in order. First, as discussed in Chapter 5, an improved international regime of safeguards and security for all separated plutonium and HEU, and ultimately for spent fuel as well, is required. The urgent problem of managing fissile materials from dismantled weapons should be used as the occasion for drawing the world's attention to building such a regime.

In the longer term, further measures to limit human access to plutonium in spent fuel—particularly older spent fuel—are desirable. There are two main options available for this purpose: *disposal* of the material in locations that are relatively physically inaccessible (such as the geologic repositories, deep boreholes, or sub-seabed options described above) or *elimination* of the material, either by fissioning or transmuting nearly all of it or by removing it essentially completely from human access (such as by shooting it into space).

Complete elimination of plutonium has received considerable attention in debates over disposition of excess weapons plutonium. As noted above, the additional costs and complexities of the elimination options for excess weapons plutonium would be of little benefit unless also applied to other accessible plutonium, including the global stock of plutonium in spent fuel. At the same time, in considering possible elimination options for that larger stock, it is essential to remember that as long as nuclear power is being produced by fission of U-235 in fuels that also contain U-238, plutonium will continue to be produced.

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Thus until nuclear power is no longer produced in this way, there cannot be a "plutonium-free world."

In general, the substantial costs of eliminating a large fraction of the global plutonium stock could not be justified if (a) the best of the nonelimination options were able to offer acceptably low proliferation risks; or (b) the steps leading to the elimination options would themselves generate security risks beyond those of the nonelimination options (as could be the case, for example, with some concepts for eliminating the plutonium by repeated reprocessing and reuse).

Given these considerations, the committee believes that a limited research program should continue to examine long-term plutonium elimination options, but that no decision to move in the direction of eliminating the large stocks of plutonium in spent fuel can be made today. The only decisions in this area facing the United States or other countries at the moment concern research priorities: none of the plausible elimination options will be ready for development or deployment decisions for years to come.

There are three main "elimination" options—that is, options for removing plutonium essentially completely from human access:

1. launching it into space, beyond earth orbit;
2. diluting it in the ocean (where it would be so dilute as to make recovery impracticable); or
3. fissioning or transmuting nearly all of the atoms of the plutonium. As with the spent fuel approach, this latter option has several variants.

Any of these three approaches would have either to address the entire mass of spent fuel (roughly 100 times greater than that of the plutonium alone) or include reprocessing on a massive, unprecedented scale to separate the plutonium from this larger mass. Both possibilities raise major complications and costs.

Space Launch

This concept has been examined in some detail for disposal of high-level waste—and rejected. It should also be rejected for plutonium.

Launching the material into low-earth orbit (which requires a velocity of about 8 kilometers per second) would not be sufficient because material in such orbits falls back to earth over time scales that are short compared to the half-life of plutonium. Therefore the material would have to be launched into an orbit around the sun unlikely to encounter the earth (which would require a velocity of the order of 11 kilometers per second), or be put on a path to fall into the sun (more than 18 kilometers per second) more than or to escape the solar system entirely (16.8 kilometers per second). Since the size of the necessary rocket increases exponentially with speed, this would multiply the cost manyfold, compared to launching the material only into low-earth orbit.

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The rockets used would have to be extremely reliable; yet the possibility of a launch explosion or a rocket failure that would result in the material reentering from space, immediately or after some time, could not be ruled out. Therefore the plutonium would have to be put in a reentry vehicle strong enough to reliably remain intact after any plausible accident, and a system might even have to be built to retrieve material left in low-earth orbit by rocket failures.

The needed reentry vehicle would probably have a mass of the order of two to three times that of the plutonium itself. The reentry vehicles would be lofted into low-earth orbit by one rocket and then given the extra velocity required to escape; hence, both the reentry vehicle and the rocket to lift it beyond its initial orbit would have to be lifted to low-earth orbit, increasing the weight that must be carried to that height by nearly another factor of ten. Thus, disposing of 50 tons of weapons plutonium in this way would require lifting more than 1,000 tons of material into low-earth orbit. Costs for such launches currently amount to some $10,000 per kilogram, which would result in a total cost in excess of $10 billion, not including any development and licensing costs. Launch costs may be greatly reduced in the future, but when one considers that the costs of the necessary development program alone would probably be comparable to the *total* cost of other options, it seems extremely unlikely that the space launch option could be made competitive, even when it is considered strictly on a cost basis.

Of course, there are many problems other than cost. Given the severe consequences if a substantial quantity of plutonium were dispersed in the atmosphere, the design of the reentry vehicle containing the plutonium would have to provide virtually perfect confidence that plutonium could not be released in the event of an accident. It is hard to imagine how the public would be convinced that such near-perfect confidence was justified, and therefore public acceptance of this option appears extremely unlikely. Moreover, assuming that the payload remained intact in the event of an accident, it would fall to earth, and its possible recovery by potential proliferators would pose a major security risk.

As noted earlier, options for going beyond the spent fuel standard to total elimination of excess weapons plutonium that involve substantial additional costs, risks, or delays are not justified unless they are applied to the much larger stock of civilian plutonium as well. In this case, including the total global spent fuel stock would greatly increase the costs and risks just described, which are already likely to be prohibitive.

Advantages: Would make plutonium essentially completely inaccessible for use in weapons.

Disadvantages: Costly, time-consuming, risky, and unacceptable to the public.

Conclusion: Does not merit government support for the plutonium disposition mission.

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Ocean Dilution

The cheapest and quickest method of making excess weapons plutonium completely irrecoverable would be to dilute it in the ocean. A single ship or submarine, equipped with long tubes through which to expel a dilute plutonium solution at great depth into large volumes of water (so that the concentration even when first put into the ocean would be within the U.S. regulatory standards for drinking water), could disperse 50 tons of plutonium into the ocean in perhaps five years. Since ships and submarines are currently being retired short of their design life, there would be no need to pay for buying one, and the direct cost would be only the expense of modifying the platform for the dilution mission and operating it for the requisite period of time. The cost of the steps required to gain approval for carrying out such an undertaking, including whatever licensing would be required, would greatly exceed the cost of actually carrying it out and are difficult to estimate.

The committee notes, however, that international standards for disposition of low-level radioactive wastes in the oceans, administered by the International Atomic Energy Agency (IAEA), include important factors not considered in the U.S. regulations, including the fact that certain ocean species consumed by human populations, such as seaweed and mollusks, accumulate plutonium in their tissues in concentrations as much as 3,000 times higher than those in the surrounding environment. With this factor included (and assumptions concerning how much of such seafood coastal populations consume, described in Appendix C), the volume of ocean into which the plutonium would have to be diluted to meet U.S. dose standards would be more than 100 million cubic kilometers, over three times the volume of the mixed surface layer of the oceans. It is extremely unlikely that the plutonium could be successfully mixed into such a large volume, with no local "hot spots" where the concentration would be significantly higher, at any reasonable level of effort. Moreover, human knowledge of physical and biological processes in the open ocean is not sufficiently complete to predict with confidence what would happen if substantial quantities of plutonium were diluted in the ocean, or to be certain that all mechanisms by which dangerous concentrations could accumulate in a local area had been ruled out. Public and international opposition to any proposal to dispose of plutonium in this way would surely be intense. If, as mentioned above, the London Dumping Convention is amended to prohibit disposal of even very dilute radioactive waste in the oceans, this option would be unambiguously banned.

Such a dilution approach would be even more out of the question if applied to the entire global stock of plutonium because far more radioactivity would be added to the ocean in that case. That problem would be more severe still if a decision were taken to dilute the entire spent fuel mass, rather than only the plutonium contained in the spent fuel, to avoid the costs of separating the plutonium from all the world's spent fuel.

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Advantages: Quick (not counting licensing and approvals); moderate cost; makes plutonium completely irrecoverable.

Disadvantages: Substantial environmental hazards; conflict with international regulations; certain public and international opposition; likely licensing and approval delays.

Conclusion: Does not merit government support for the plutonium disposition mission.

Fission and Transmutation

Since neither space launch nor ocean dilution is acceptable, technologies designed to fission or transmute nearly 100 percent of the plutonium are the only plausible elimination approaches. Plutonium destruction fractions greater than 80 percent appear attainable only with the help of fuel reprocessing and plutonium recycle. With such repeated reprocessing and reuse, virtually any type of reactor could in principle be used in an elimination option: while only fast-neutron reactors can fission all isotopes of plutonium, reactors with a thermal neutron spectrum, such as LWRs, can in principle transmute those isotopes they cannot fission into other isotopes they can, as part of their normal operations.

Policymakers considering these elimination options should be under no illusions concerning the scale of the effort required. Completing a program to burn a large fraction of the world's plutonium stocks to 99 percent or more—including developing, deploying, and operating the necessary technologies and facilities—would cost tens or hundreds of billions of dollars and take many decades or even centuries.

The time required is a complex function of the percentage of plutonium consumed in each reactor cycle; the fraction of the plutonium in the fuel cycle that is actually in the reactor where it can be consumed; and the amount of plutonium lost to waste in processing. In the simplified calculations currently being done, which do not include reactor development and construction time, the period required to achieve such destruction fractions is not dependent on the total amount of plutonium to be destroyed; rather, the amount of plutonium determines the reactor capacity required to meet these schedules.

Consider, for example, a simple case in which a hypothetical reactor system were capable of consuming 10 percent of the plutonium in its core each year, and the amount of plutonium in the supporting fuel cycle (awaiting reprocessing, in fuel fabrication, and the like) were equal to the amount in the reactor core. In this simple case, if there were no processing losses, 5 percent of the total remaining amount of plutonium in the system would be consumed each year. But because that total remaining amount would be declining constantly, the amount of plutonium consumed each year would also decline. Under this hypothetical model, it would take some 90 years before 99 percent of

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the plutonium was destroyed.[45] If one considered the fact that some plutonium would be lost to waste on each reprocessing cycle, the 99 percent destruction figure might never be achieved—depending on the effectiveness of the reprocessing technology in reducing such losses. Such simple calculations indicate that the current design of the Advanced Liquid Metal Reactor would take hundreds of years to reduce stockpiles of plutonium and other transuranics by 99 percent. The accelerator-based conversion (ABC) concept could in principle achieve comparable results in decades rather than centuries (because of its much smaller reactor and reprocessing inventories), but to do so would involve several major challenges (see below). Thus, such an approach would require a commitment of unprecedented length and, at least for the near term, substantial subsidies. Institutional arrangements lasting many decades or even centuries would be required to manage such an effort.[46]

Whether or not such a plutonium elimination approach should be pursued is a subject integrally tied to the future of nuclear power and fuel cycles, going well beyond the committee's charge. If it were to be pursued, it is premature to select a particular reactor system as the preferred option for this purpose. The National Research Council's Panel on Separations Technology and Transmutation Systems (STATS) is considering various options for nearly complete elimination of actinides (and possibly some long-lived fission products) as a waste treatment approach (known as actinide burning). The committee benefited greatly from discussions of the STATS panel's work. Its report, expected in 1994, should provide a useful basis for setting policy and research priorities in this area. Here, the committee confines itself to brief remarks on the various options:

LWRs. Though today LWRs are only rarely considered for this role, the technology—by far the most widely demonstrated and well-understood approach to nuclear power—could in principle be used for actinide burning, by repeatedly reprocessing their spent fuel and recycling it as MOX. With suitable reprocessing, 100 percent MOX-fueled LWRs could consume plutonium somewhat faster per unit of thermal reactor power than MOX-fueled liquid-metal reactors. Complex issues would arise concerning the buildup of less desirable isotopes after repeated recycling, which is also the case with several of the other

[45] Considering only the percentage of the *original* actinides destroyed is somewhat unfair to the actinide burning concept, since the actinide burners would produce electricity, that might otherwise be produced by LWRs operating on a once-through cycle, which would create an ever-increasing stockpile of actinides to be dealt with. Thus, a fairer approach is to compare the time-dependent inventory of actinides in the actinide burner concepts to the ever-increasing inventory that would be created by LWRs providing an equal amount of electricity. This somewhat shortens the time required to reach a given destruction percentage.

[46] See Lawrence Ramspott et al., "Impacts of New Developments In Partitioning and Transmutation on the Disposal of High-Level Nuclear Waste in a Mined Geologic Repository," Lawrence Livermore National Laboratory, UCRL-ID-109203, March 1992. For a comparison of the fraction of actinide inventory destroyed as a function of time for various concepts, see Jor-Shan Choi and Thomas Pigford, "Inventory Reduction Factors for Actinide Burning," unpublished paper.

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options described below. The repeated reprocessing and reuse of separated plutonium would raise significant proliferation risks, and this approach is therefore probably not desirable if the primary goal is to reduce overall security risks. Similar remarks apply to CANDU reactors.

LMRs. Liquid-metal reactors, with their fast-neutron spectrum, can fission all isotopes of plutonium and are frequently put forward as a prime candidate for nearly complete plutonium elimination. Several countries are examining their potential as actinide burners. As noted above, some advanced LMRs, such as that being researched in the United States, employ an integral reprocessing technique in which the plutonium is never fully separated, mitigating some of the safeguards concerns that would otherwise arise from the repeated reprocessing and recycling required for the elimination option.

Nonfertile Fuels. The net rate of plutonium destruction would be increased somewhat if additional plutonium were not produced during reactor operations. This could be accomplished with the use of fuels that do not contain isotopes that produce fissile materials when they absorb neutrons (as the U-238 in typical reactor fuels today does). Since they do not "breed" fissile materials, these are known as "nonfertile" fuels. Several concepts for such fuels have been proposed, all of which would require considerable development, both for the fuels themselves and to address reactor safety issues involved in their use.

The advantage offered by such fuels for a plutonium destruction campaign may be less than is commonly thought. This is because even without such nonfertile fuels, simply increasing the plutonium concentration in ordinary fertile fuels would substantially reduce the amount of new plutonium produced for a given amount of energy generated (or for a given amount of weapons plutonium burned).

For example, doubling the plutonium concentration in fuel (for example, 3.5 to 7 percent of heavy-metal atoms in MOX fuel for an LWR) would require, if the power level were to be kept the same, that the neutron flux in the fuel be lowered by a factor of two, by using control absorbers and neutron poisons. This lowered neutron flux would reduce the rate of production of new plutonium by about a factor of two (a bit more, actually, because the extra plutonium loading in the fresh fuel replaces fertile U-238 atoms). Higher initial plutonium loadings would reduce that rate still further. Thus, fertile fuels with high fissile loadings (such as might be used in liquid-metal reactors, for example) can reduce the production of new plutonium substantially.

Since, in addition, even nonfertile fuels cannot burn their plutonium content down to zero (because at low enough concentrations of plutonium in relation to neutron-absorbing fission products, a chain reaction can no longer be sustained), it seems unlikely that the development of such fuels for reactors not already designed to use them (the HTGR being the main example of a reactor type designed to employ nonfertile fuels) could provide an advantage large enough to justify the required level of effort.

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Accelerator-based Conversion (ABC). Accelerator-based conversion (ABC) systems have been under study as a means of eliminating plutonium, and of fissioning actinides and transmuting fission products in order to reduce the longevity of radioactive wastes. In this concept, a reactor that was subcritical—meaning that the neutrons within it could not sustain a chain reaction without outside input—is driven by neutrons produced by a beam of particles from an accelerator hitting a target. In the concepts that have received most examination, the subcritical reactor would have a fluid fuel (either an aqueous slurry or a molten salt) that would be fed continuously out of the reactor, reprocessed to remove fission products, and fed back into the reactor.[47]

This option is only at the early paper-study stage and cannot be available on a large scale for decades. Both the proposed subcritical fluid fuel reactor technology and its fuel cycle technology are extremely challenging and unproven. The reactor, for example, would have a radiation flux of order 10 times that in current LWRs, raising serious engineering issues concerning the survival of the reactor materials. Reprocessing would take place within days or weeks after the fuel left the reactor, forcing the approach to deal with unprecedented levels of radioactivity; at the same time, proponents claim that reprocessing losses would be unprecedentedly low. If the estimated performance could be attained, however, such systems could destroy plutonium at a rate (per unit of thermal energy) comparable to those of the other destruction-oriented options and could reach high reduction factors for plutonium inventory more rapidly than many of the other options.

The continuous on-line reprocessing proposed for ABC would offer some advantages in waste reduction and in safeguards against plutonium theft or covert diversion (but again, probably not against open diversion by the system's operators)—shared in varying degrees by other advanced systems that use such reprocessing.

Molten-Salt Reactors. Molten-salt reactors, based on the system explored in the 1950s-era Molten Salt Reactor (MSR) Experiment have also been proposed as destroyers of plutonium. This concept is similar in many respects to the molten-salt ABC, except that the reactor is fully critical and therefore no accelerator is required. Proponents claim that MSRs offer major safety advantages over existing light-water reactor technology. However, like ABC, MSRs would take decades to develop, license, and deploy.

Pebble-Bed Reactors. Pebble-bed reactors (PBRs), originally developed for nuclear rocket applications, have also been proposed for use as plutonium destroyers. Like ABC and molten-salt systems, they are in the early stages of development.

[47] Solid-fuel concepts have also been examined but are perceived as not having some of the advantages of the fluid fuel approach.

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Modular High-Temperature Gas-Cooled Reactors (MHTGRs). In principle, the MHTGR could also be used in an elimination mode, by reprocessing and recycling its spent fuel. Reprocessing this fuel would be complex, however, and MHTGR advocates have not pursued this approach in recent years.

As indicated above, it is too soon to choose among these options. Additional research is desirable to clarify the issues involved in elimination options in general and to identify the most promising options for that purpose.

CONCLUSIONS

Figure 6-5 summarizes the committee's judgments concerning the long-term disposition options described in this chapter. Any figure of this kind can only be an illustrative overview of the options and issues; by their nature, such figures are oversimplifications. Moreover, these ratings are inevitably judgmental. The committee chose to use only three ratings—high, moderate, and low—because the information available cannot confidently support more detailed assessments. This inevitably means that there may be wide variations among options that receive the same rating; two options might each be expensive enough to be rated as having "high" cost, for example, but one might be several times as expensive as the other.

The committee has not attempted to reach an "overall" rating for each option, since readers may rank the criteria differently. Such an overall rating cannot be reached simply by averaging highs and lows across columns. For example, as described earlier, the committee does not consider indefinite storage an acceptable option, because the black mark under "risks of recovery"—with all it implies for the risks of theft, breakout, and the arms control and nonproliferation regimes—more than outweighs the low risks and costs of this option.

Criteria. All the criteria are described in the negative, so that "high" corresponds to high risks or costs, whereas "low" is a more favorable rating.

The first three columns of the chart are all related to the speed with which an option could be accomplished, which the committee considers to be one of the principal criteria for choice (discussed under "Risks of Storage" in the text). "Technical Uncertainty" affects both timing and the degree of assurance of success, as does the following column, "Difficulty of Public/Institutional Acceptance." The latter category includes licensing and public approval issues, and, where necessary, issues related to the approval of international parties. The third column, "Time to Execute," refers to the time required for implementation once the obstacles represented by the first two columns have been overcome—that is, once development is complete and the requisite licenses and approvals have been obtained. This includes the time required for any necessary facility construction or modification, and the time during which the option would be processing the excess plutonium stock.

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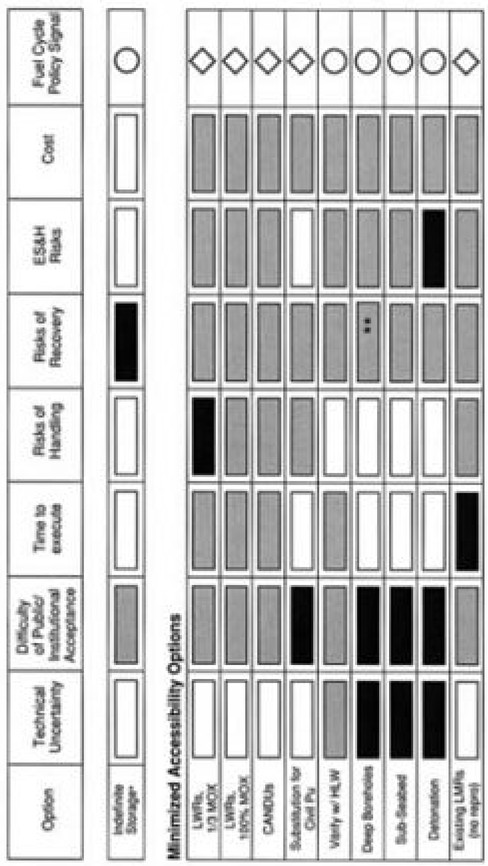

FIGURE 6-5 Comparison of options for long-term disposition of weapons plutonium

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Minimized Accessibility Options (*continued*)

ALWRs	Low	Moderate	High	Moderate	Moderate	Moderate	Moderate	◇
New LMRs (no repro)	Moderate	Moderate	High	Moderate	Moderate	Moderate	High	◇
MHTGRs	Moderate	Moderate	High	Moderate	Moderate	Moderate	High	◇

Elimination Options

Ocean Dilution	Moderate	High	Moderate	Moderate	Low	High	Moderate	○
Space Launch	High	High	Moderate	Moderate	Low	High	High	○
LWRs or CANDUs (w/ repro)	Moderate	High	High	High	Low	High	High	◇
LMRs (w/ repro)	Moderate	High	High	Moderate	Low	Moderate	High	◇
MHTGRs (w/ repro)	High	High	High	High	Low	High	High	◇
ABC	High	High	High	Moderate	Low	Moderate	High	◇
MSR, PBR	High	High	High	Moderate	Low	Moderate	High	◇

Key: Low / Moderate / High

◇ *US supports use of plutonium fuels, at least for this mission.*

○ *US does not support use of plutonium fuels.*

* Both security and ES&H risks of storage would increase dramatically if political arrangements governing storage collapsed.

** Plutonium in boreholes is more recoverable than plutonium in spent fuel by the nation in control of the borehole site, but not by potential proliferators.

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As in the text, "Risks of Handling" refers to the risks of theft or diversion of materials during the various processes involved before the material reaches its final state, while "Risks of Recovery" refers to the risks that the material might be recovered for weapons use (by the state from whose weapons it came or by others) after disposition was complete. Hence, the latter, combined with the several timing criteria, effectively portrays the committee's judgment of the option's political impact on arms reduction and nonproliferation (assuming that equivalent levels of transparency would be applied to all options); this impact does not receive a separate column in the chart.

The "ES&H Risk" and "Cost" categories are self-explanatory. The final column, "Fuel Cycle Policy Signal," refers to the issue relating to more general U.S. fuel cycle and nonproliferation policies described in the text: those options involving the use of weapons plutonium in reactors would send the signal that the United States approved of such use, at least for this limited purpose, whereas the disposal options would send the signal that even for the pressing problem of plutonium disposition, the United States did not approve of the use of plutonium fuels. In this column, therefore, the committee simply indicates whether the option would or would not use plutonium in reactor fuel, rather than attempting a high, moderate, and low categorization.

Ratings. For all the criteria other than "Technical Uncertainty," the option of using 100 percent MOX fuel in U.S. LWRs is used as the standard for a moderate rating. (Technical uncertainty for the LWR MOX option is rated low.) Options that involve greater risks or costs than MOX in LWRs are rated high, while those that involve significantly lower risks or costs are rated low.

Options

Indefinite Storage

Indefinite storage is among the more complex options to rate, because for the next several decades storage would be relatively simple, safe, and low cost (at least in the United States), but these judgments would change if it were truly extended indefinitely.

Indefinite storage is rated as having low technical uncertainty and time to execute because storage can be (and is being) implemented immediately. Storage is rated as low in risks of handling and ES&H risks (because no processing is involved), and low in cost (by assuming costs comparable to those at Pantex, rather than commercial charges for plutonium storage). The difficulty of obtaining public and institutional acceptance is rated moderate, although it would probably be quite difficult to gain public approval for storage that was explicitly presented as lasting indefinitely, at least in the United States. Indefinite storage is the only option on the chart rated as having high risks of recovery, since the

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material could be removed from the storage site and used for weapons at any time.

Minimized Accessibility

LWRs with 1/3 MOX refers to the use of existing or modified LWRs, either U.S. LWRs using U.S. plutonium or Russian VVER-1000s using Russian plutonium. These are rated as having low technical uncertainty. They are rated moderate in most other categories, but high under risks of handling, because the material would have to be transported to three times as many sites as in the case of LWRs with 100 percent MOX cores. As described in the text, there are likely to be higher risks of handling in the former Soviet Union under present circumstances than in the United States.

LWRs with 100 percent MOX (which, like the previous entry, refers to the use of existing or partly completed LWRs, in this case with modifications as necessary for use of full-MOX cores) are rated moderate in all categories except technical uncertainty, which remains low, as in the case of LWRs with one-third MOX, because the modifications needed to accommodate full-MOX cores are not sufficient to create substantial uncertainties or require major development.

CANDUs, like full-MOX LWRs, are rated moderate under all criteria except technical uncertainty, which is rated low, because this option would not require a major development program. The moderate rating for difficulty of acceptance is more doubtful than in the case of LWRs, since Canadian acceptance of plutonium fuel use remains uncertain. Similarly, the cost rating for CANDU reactors is more uncertain.

Substitution for civil plutonium is rated high for difficulty of acceptance, because of the complex web of arrangements that would have to be changed to implement this option, but low for time to execute, because the scale of MOX use already planned is large enough to consume 50 or 100 tons of weapons plutonium quite rapidly if this option were agreed to. ES&H risks are rated low because there would be virtually no *net additional* risks compared to the plutonium use already planned; risks of handling would be rated low for the same reason, except that there is some significant difference in theft and diversion risk in the shift from reactor-grade to weapons-grade plutonium, and there are the risks of transport of the plutonium from its current location. Hence the risks of handling are rated moderate.

Vitrification with high-level waste is rated moderate on all criteria except risks of handling, where it is rated low, because of the somewhat greater ease of safeguarding described in the text. The technical uncertainty, which is moderate, is greater than in the case of the reactor options just described. Although time to execute is also rated as moderate, vitrification might be accomplished somewhat more rapidly than the LWR and CANDU options if technical uncertainties are resolved.

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Deep boreholes are rated high on technical uncertainty because they would require more development than either the existing reactor options or the vitrification option. They are rated high for difficulty of public and institutional acceptance because of the likely difficulties of obtaining the necessary licenses. Boreholes are rated as having moderate risks of recovery, with the caveat that recovery would be less difficult for the state in control of the borehole site than would recovery of plutonium in spent fuel. Although the cost of implementation itself would probably rate as low, boreholes are rated moderate on cost because of the development and licensing programs required. These costs could in fact ultimately be in the high category (as is also the case with other nonrepository disposal options). Boreholes are judged moderate on ES&H risks, but if technical uncertainties are resolved favorably, these risks could turn out to be low.

Sub-seabed disposal is rated high in technical uncertainty because considerable development would still be required before this option could be implemented—but it is the most fully developed of the options receiving this rating. This approach is rated as having high difficulty of public and institutional acceptance, because of the legal barriers and likely intense international opposition to such disposal. As with deep-borehole disposal, however, time to execute and risks of handling are rated low, and cost is rated moderate because even though implementation costs could be low, the costs of development and licensing would be substantial.

Detonation with underground nuclear explosions is rated high for technical uncertainty, even though it is clear it could be done, because of the many unresolved safety and environmental issues. Similarly, it is rated as having high ES&H risks and acceptance difficulties.

Existing LMRs without reprocessing are less susceptible to across-the-board ratings than some of the other options because there are wide variations in the design and characteristics of these facilities; moreover, some are in countries where the excess weapons plutonium is located, whereas for others, the plutonium would have to be shipped and agreements negotiated. Existing LMRs are rated as low in technical uncertainty because the use of plutonium in these reactors is amply demonstrated; however, there are outstanding technical issues regarding the safety of some of these facilities. The time necessary to execute is rated high, because of the relatively small capacity, advanced age, or poor availability records of the existing LMRs.

ALWRs refers to LWRs built for this mission, whether existing or follow-on designs. Technical uncertainty is rated low (though this judgment applies primarily to existing and evolutionary designs). Time to execute is rated high because licensing and building new reactors would take substantially longer than using existing facilities.

New LMRs (without reprocessing) and *MHTGRs* are rated high on time to execute and cost, because of the delays and costs of development, licensing, and construction for these advanced reactors, both of which are estimated to involve higher life cycle costs in the current market than evolutionary LWRs.

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Elimination

Ocean dilution is rated as having high technical uncertainty, because although it is clear it could be done, there are large uncertainties concerning the ultimate ecological impact. It is rated moderate for cost, although the cost of implementation would be low, because of the likely costs of developing the option and attempting to gain approval for it.

Space launch is rated high for ES&H risks, because of the risks involved in possible launch accidents, but this rating could be reduced with a payload design that provided high-confidence plutonium containment for all plausible accidents.

LWRs or CANDUs with reprocessing are rated as having high time-to-execute and costs (as are all of the other reactor reprocessing options) because of the very long time required to eliminate nearly all of the plutonium by this means, and the high costs of reprocessing and recycle. Technical uncertainty is rated as moderate because the plutonium use demonstrated to date has not involved multiple-recycle fuel with its different mix of isotopes. Risks of handling are rated as high, because these options would involve repeated separation, transport, and use of separated plutonium, while several of the other reprocessing options are or can be designed to maintain the plutonium in a more theft-resistant form. ES&H risks are rated as high because of the record of ES&H impacts of reprocessing in some countries, but the committee notes that appropriate application of resources would greatly reduce these risks.

LMRs with reprocessing are also rated as having moderate technical uncertainty, because while some of these systems are being designed for a similar actinide-burning mission, considerable development is still required. Their handling and ES&H risks are rated as only moderate, rather than high, on the assumption that new reprocessing techniques that reduce wastes and safeguards risks would be employed.

MHTGRs with reprocessing are rated as having high technical uncertainty, since a reprocessing approach has not been pursued for HTGRs in recent years, and such a plutonium elimination objective has not been examined in detail. Like LWRs and CANDUs with reprocessing, they are rated as having high risks of handling, because of the repeated reprocessing and use of fully separated plutonium that would be required. ES&H risks are rated as high, on the analogy to LWRs and CANDUs with reprocessing, but the same caveat applies.

ABC is rated as having high technical uncertainty, because of the large amount of technical development still required. It is rated moderate for ES&H risk, but that judgment is quite uncertain: if ABC fulfills its proponents' expectations, ES&H risk could be quite low, but it is also possible that unexpected ES&H risks could arise.

MSR and *PBR* receive the same ratings across the board as ABC, for much the same reasons. It is too soon to tell which of these technologies would be

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preferable for the missions their advocates propose, if these missions are pursued.

RECOMMENDATIONS

- It is important to begin now to build consensus on a road map for decisions concerning long-term disposition of excess weapons plutonium. Because disposition options will take decades to carry out, it is critical to develop options that can muster a sustainable consensus.
- Storage should not be extended indefinitely, because of (1) the negative impact that maintaining this material in forms readily accessible for weapons use would have on nonproliferation and arms reduction, (2) the risk of breakout and (3) the risks of theft from the storage site. One of the key criteria by which disposition options should be judged is the speed with which they can be accomplished, and thus the degree to which they curtail the risks of prolonged storage.
- Disposition options beyond storage should be pursued only if they reduce overall security risks compared to leaving the material in storage, considering both the final form of the material and the risks of the various processes required to get to that state. In the current unsettled circumstances in Russia, this minimum criterion is a significant one.
- The United States and Russia should begin discussions with the aim of agreeing that whatever disposition options are chosen, an agreed, stringent standard of accounting, monitoring, and security will be maintained throughout the process—coming as close as practicable to meeting the standard of security and accounting applied to intact nuclear weapons.
- Disposition options should be designed to transform the weapons plutonium into a physical form that is at least as inaccessible for weapons use as the much larger and growing stock of plutonium that exists in spent fuel from commercial nuclear reactors. The costs, complexities, risks, and delays of going further than this "spent fuel standard" to eliminate the excess weapons plutonium completely or nearly so would not be justified unless the same approach were to be taken with the global stock of civilian plutonium.
- The two most promising alternatives for the purpose of meeting the spent fuel standard are:

1. The *spent fuel option*, which has several variants. The principal one is to use the plutonium as once-through fuel in existing commercial nuclear power reactors or their evolutionary variants. Candidates for this role are U.S. light-water reactors (LWRs), Russian LWRs, and Canadian deuterium-uranium (CANDU) reactors. The use of European and Japanese reactors already licensed

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for civilian plutonium should also be considered for Russian weapons plutonium.

2. The *vitrification option*, which would entail combining the plutonium with radioactive high-level wastes (HLW) as these are melted into large glass logs. The plutonium would then be roughly as difficult to recover for weapons use as plutonium in spent fuel.

   A third option, *burial in deep boreholes*, has until now been less thoroughly studied than alternative 1 and 2, but could turn out to be comparably attractive.

- A coordinated program of research and development should be undertaken immediately to clarify and resolve the uncertainties the committee has identified regarding each of these three options. The aim should be to pave the way for a national discussion, with full public participation, in order to make a choice within a very few years.
- Applying the spent fuel standard narrows the options considerably:

1. Options that irradiate the weapons plutonium in reactors only briefly ("spiking"), leaving it far less radioactive than typical spent fuel, and with little change in its isotopic composition, should not be pursued except possibly as a preliminary step on the road toward the spent fuel option. (Even for that purpose, in those cases the committee has examined, the possible advantages of the spiking option over continued storage do not appear to be worth the substantial cost of such spiking approaches.)
2. Options that involve *only* a chemical barrier to reuse—such as vitrification of plutonium without HLW or other fission products—should not be pursued, except possibly as a first step toward adding radiological or physical barriers as well.
3. Advanced reactors should not be specifically developed or built for transforming weapons plutonium into spent fuel, because that aim can be achieved more rapidly, less expensively, and more surely using existing or evolutionary reactor types.
4. Options that strive to destroy a large fraction of the plutonium without reprocessing and recycle, using existing or advanced reactors with nonfertile fuels, should not be pursued because such approaches cannot destroy enough of the plutonium to obviate the need for continuing safeguards, and the modest reduction in security risk that could be achieved is not worth the extra delay, cost, and uncertainty that development of such approaches would entail.

- Production of tritium should not be a major criterion for choosing among disposition options.
- Institutional issues in managing plutonium disposition are complex and the process to resolve them must be carefully managed. The process must provide adequate safeguards, security, and transparency, as well as protection for

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the environment, safety, and health; obtain public and institutional approval, including licenses; and allow adequate participation in the decision making by all affected parties, including the U.S. and Russian publics and the international community. Adequate information must be made available to give substance to the public's participation.

- Although the committee did not conduct a comprehensive examination of the proliferation risks of civilian nuclear fuel cycles, which would have gone beyond its charge, the risks posed by all forms of plutonium must be addressed.
- While the spent fuel standard is an appropriate goal for next steps, further steps should be taken to reduce the proliferation risks posed by *all* of the world's plutonium stocks, military and civilian, separated and unseparated; the need for such steps exists already, and will increase with time. Options for near-total elimination of plutonium may have a role to play in this effort, and research on defining and exploring these options should be continued at a conceptual level. These options, however, can only realistically be considered in the broader context of the future of nuclear electricity generation, including the minimization of security and safety risks—the assessment of which is beyond the scope of this report. Studies of that broader context should have as one important focus minimizing the risk of nuclear proliferation, and should consider nuclear systems as a whole, from the mining of uranium through to the disposal of waste; should consider feasible safeguarding methods as elements of development and design; and should take an international approach, realizing that other nations' approaches reflect their differing economic, political, technical, security, and geographic situations and perceptions.

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7

Recommendations

The committee's work on the issues of plutonium management and disposition has led it to the following four principal recommendations:

1. *A New Weapons and Fissile Materials Regime*. The committee recommends that the United States work to reach agreement with Russia on a new, reciprocal regime that would include

(a) declarations of stockpiles of nuclear weapons and all fissile materials;
(b) cooperative measures to clarify and confirm those declarations;
(c) an agreed halt to the production of fissile materials for weapons; and
(d) agreed, monitored net reductions from 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.

2. *Safeguarded Storage*. The committee recommends that the United States and Russia pursue a reciprocal regime of secure, internationally monitored storage of fissile material, with the aim of ensuring that the inventory in storage can be withdrawn only for non-weapons purposes.
3. *Long-Term Plutonium Disposition*. The committee recommends that the United States and Russia pursue long-term plutonium disposition options that:

(a) minimize the time during which the plutonium is stored in forms readily usable for nuclear weapons;

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(b) preserve material safeguards and security during the disposition process, seeking to maintain the same high standards of security and accounting applied to stored nuclear weapons;
(c) result in a form from which the plutonium would be as difficult to recover for weapons use as the larger and growing quantity of plutonium in commercial spent fuel; and
(d) meet high standards of protection for public and worker health and for the environment.

The two most promising alternatives for achieving these aims are

- fabrication and use as fuel, without reprocessing, in existing or modified nuclear reactors; or
- vitrification in combination with high-level radioactive waste.

A third option, burial of the excess plutonium in deep boreholes, has until now been less thoroughly studied than have the first two options, but could turn out to be comparably attractive.

4. *All Fissile Material.* The committee recommends that the United States pursue new international arrangements to improve safeguards and physical security over all forms of plutonium and HEU worldwide. In particular, new cooperative efforts to improve security and accounting for all fissile materials in the former Soviet Union should be an urgent priority.

- The president should establish a more systematic process of interagency coordination to deal with the areas addressed in this report, with sustained top-level leadership.

DECLARATIONS AND DISMANTLEMENT

- The United States and Russia should make formal commitments that specific quantities of fissile material from dismantled weapons (representing a very large fraction of those materials) will be declared excess and committed to non-weapons use or disposal. Storage and disposition of these materials should be subject to agreed standards of accountability, transparency, and security. The standards for accountability and security should approximate as closely as possible the stringent standards applied to stored nuclear weapons.
- The United States should negotiate with Russia to create, through a step-by-step process, a broad regime under which each side's stocks of nuclear weapons and fissile materials would be declared and monitored, and the size of both stocks would be verifiably reduced over time in line with current reductions in deployed delivery systems. This regime would include, in addition to the fissile material steps mentioned in the previous recommendation:

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1. a system of mutual declarations of total inventories of nuclear weapons and of fissile materials in civilian and military inventories;
2. measures designed to increase confidence in the accuracy of the declarations, and the transparency of each side's nuclear weapons production complexes, including physical access to production facilities and production records for fissile materials;
3. a monitored cutoff of production of HEU and plutonium for weapons. If necessary, the United States should be willing to provide limited funding to assist Russia in the measures necessary to cut off plutonium production; and
4. an agreement providing for perimeter-portal monitoring of dismantlement facilities, counting warheads entering these facilities and assaying the fissile material that leaves. If the *net* subtractions from each side's stockpile are to be confirmed, some monitoring of warhead assembly will be required as well.

- Information concerning the total stockpiles of weapons and fissile materials, and those weapons characteristics necessary for external monitoring, should be declassified as part of this transparency regime. Appropriate reviews to prepare for such declassification should be initiated promptly.
- Russia and the United States should dismantle their retired warheads as expeditiously as is practical, consistent with protection for the environment, safety, and health, and cost-effectiveness.

INTERMEDIATE STORAGE

- The United States and Russia should place plutonium excess to military needs in safeguarded storage as soon as practical.
- Stored excess fissile materials committed to non-weapons use or disposal by the United States and Russia should be placed under international safeguards (possibly combined with bilateral monitoring). In the interest of speed, monitoring of storage could initially be a bilateral U.S.-Russian effort, but the IAEA should be brought into the process rapidly.
- The United States should continue providing assistance for a Russian fissile material storage facility, which should be designed to consolidate all excess weapons materials at a single site, to facilitate security and international monitoring.
- Plutonium from dismantled weapons should continue to be stored as intact pits for now. Deformation of these pits and perhaps other steps to reduce the rearmament risk should be given serious consideration, and should be undertaken if they can be accomplished at relatively low cost and ES&H risk.

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- Pits should be stored in sealed containers, with monitors permitted to assay the containers externally without observing the pits' dimensions, to provide adequate safeguards without compromising sensitive weapons design information.
- Once definite disposition options have been chosen, the plutonium should be converted expeditiously to whatever form is required as part of the disposition process.
- Financial or other incentives might be provided to encourage Russia to place the maximum amount of material into monitored storage. With the condition that these not be an open-ended commitment or provide any incentive for continued production of separated plutonium, such incentives would be desirable and should continue to be explored.
- The safeguards budget of the IAEA should be substantially increased, and other steps should be taken to strengthen that organization's ability to carry out its critical responsibilities. One promising approach would be the creation of a voluntary fund, to which nations interested in improved safeguards would make contributions above and beyond their fixed allocations.
- Appropriate arrangements for intermediate storage are to a large extent decoupled from long-term disposition decisions and should be considered more urgent.

DISPOSITION

- It is important to begin now to build consensus on a road map for decisions concerning long-term disposition of excess weapons plutonium. Because disposition options will take decades to carry out, it is critical to develop options that can muster a sustainable consensus.
- Storage should not be extended indefinitely, because of (1) the negative impact that maintaining this material in forms readily accessible for weapons use would have on nonproliferation and arms reduction, (2) the risk of breakout and (3) the risks of theft from the storage site. One of the key criteria by which disposition options should be judged is the speed with which they can be accomplished, and thus the degree to which they curtail the risks of prolonged storage.
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to get to that state. In the current unsettled circumstances in Russia, this minimum criterion is a significant one.

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2. The *vitrification option*, which would entail combining the plutonium with radioactive high-level wastes (HLW) as these are melted into large glass logs. The plutonium would then be roughly as difficult to recover for weapons use as plutonium in spent fuel.

A third option, *burial in deep boreholes*, has until now been less thoroughly studied than alternative 1 and 2, but could turn out to be comparably attractive.

- A coordinated program of research and development should be undertaken immediately to clarify and resolve the uncertainties the committee has identified regarding each of these three options. The aim should be to pave the way for a national discussion, with full public participation, in order to make a choice within a very few years.
- Applying the spent fuel standard narrows the options considerably:

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change in its isotopic composition, should not be pursued except possibly as a preliminary step on the road toward the spent fuel option. (Even for that purpose, in those cases the committee has examined, the possible advantages of the spiking option over continued storage do not appear to be worth the substantial cost of such spiking approaches.)

2. Options that involve *only* a chemical barrier to reuse—such as vitrification of plutonium without HLW or other fission products—should not be pursued, except possibly as a first step toward adding radiological or physical barriers as well.
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4. Options that strive to destroy a large fraction of the plutonium without reprocessing and recycle, using existing or advanced reactors with nonfertile fuels, should not be pursued because such approaches cannot destroy enough of the plutonium to obviate the need for continuing safeguards, and the modest reduction in security risk that could be achieved is not worth the extra delay, cost, and uncertainty that development of such approaches would entail.

- Production of tritium should not be a major criterion for choosing among disposition options.
- Institutional issues in managing plutonium disposition are complex and the process to resolve them must be carefully managed. The process must provide adequate safeguards, security, and transparency, as well as protection for the environment, safety, and health; obtain public and institutional approval, including licenses; and allow adequate participation in the decision making by all affected parties, including the U.S. and Russian publics and the international community. Adequate information must be made available to give substance to the public's participation.

TOTAL PLUTONIUM INVENTORIES

- Although the committee did not conduct a comprehensive examination of the proliferation risks of civilian nuclear fuel cycles, which would have gone beyond its charge, the risks posed by all forms of plutonium must be addressed.
- While the spent fuel standard is an appropriate goal for next steps, further steps should be taken to reduce the proliferation risks posed by *all* of the world's plutonium stocks, military and civilian, separated and unseparated; the need for such steps exists already, and will increase with time. Options for near-total elimination of plutonium may have a role to play in this effort, and research on defining and exploring these options should be continued at a con

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ceptual level. These options, however, can only realistically be considered in the broader context of the future of nuclear electricity generation, including the minimization of security and safety risks—the assessment of which is beyond the scope of this report. Studies of that broader context should have as one important focus minimizing the risk of nuclear proliferation, and should consider nuclear systems as a whole, from the mining of uranium through to the disposal of waste; should consider feasible safeguarding methods as elements of development and design; and should take an international approach, realizing that other nations' approaches reflect their differing economic, political, technical, security, and geographic situations and perceptions.

- Urgent steps are needed to improve safeguards and security for all fissile materials in the former Soviet Union, including materials beyond those considered excess. The committee recommends a comprehensive approach at a significantly higher level of funding, with an emphasis on cooperation in addressing the most immediate risks. Western countries, including the United States, should press Russia and the other states of the former Soviet Union to take a number of steps urgently, and should be willing to provide necessary equipment and funds for these purposes. In particular, Western countries should press for and offer assistance for:

1. immediate installation of appropriate portal-monitoring systems to detect any theft of fissile materials, as well as adequate armed guard forces, at *all* sites where enough weapons-usable fissile material to make a nuclear weapon is stored;
2. an urgent program of security and accounting inspections and improvements at all of these sites;
3. improved economic conditions for personnel responsible for accounting and security for weapons and fissile materials, to reduce incentives for corruption and insider theft;
4. improved national oversight of security and safeguards, with a strengthened basis in law. In Russia, this would involve strengthening the role of GOSATOMNADZOR, while in other former Soviet states it would involve strengthening or creating comparable organizations;
5. consolidation of fissile material storage and handling where possible;
6. conversion of research reactors to run on low-enriched uranium fuels, reducing the number of sites where weapons-grade fissile materials are used;
7. greater Western participation and cooperation in safeguards and security, ideally at all fissile material sites, but at all civilian sites at a minimum; and
8. regularized, as well as emergency, working-level cooperation in monitoring reports of alleged diversions.

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- The steps outlined by the committee to improve safeguards and physical security for fissile materials in the United States and Russia should set a standard for a regime for improved management of such materials in civilian use throughout the world. Negotiations should be pursued to:

1. create a global cutoff of all unsafeguarded production of fissile materials;
2. use the U.S.-Russian safeguarded storage regime recommended above as a base for a broad international storage and management regime for fissile materials, including registration and safeguards for all civilian separated plutonium and HEU;
3. extend the U.S.-Russian declaratory regime mentioned above to a global regime of public declarations of stocks of fissile materials;
4. agree on higher standards of physical security for these materials, with an international organization given authority to inspect sites to monitor whether the standards are met; and
5. agree on cooperative international approaches to manage reprocessing and use of plutonium to avoid building up excess stocks.

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Appendix A

List of Principal Briefings

November 20-22, 1992: Committee on International Security and ArmsControl (CISAC) Meeting, Irvine, California

Department of Energy (DOE) Plutonium Disposition Studies and Activities; Plutonium Storage Plans; Reactor Options; Vitrification Options; Nunn-Lugar Cooperation Programs.

Briefers: Sol Rosen (DOE, Office of Nuclear Energy); John Herczeg (DOE, Office of Nuclear Energy); Andrew Bieniawski (DOE, Office of Arms Control and Nonproliferation); William Sprecher (DOE, Office of Civilian Radioactive Waste Management); others.

January 11-13, 1993: CISAC and Reactor Panel Meeting, WashingtonD.C.

Vitrification Options; Plutonium Storage Approaches; Plutonium Storage Forms; Nunn-Lugar Cooperation Programs; International Atomic Energy Agency Safeguards; International Plutonium Storage Concepts; DOE Plutonium Disposition Studies; Advanced Light-Water Reactors; Accelerator-Based Conversion; Modular High-Temperature Gas-Cooled Reactors; Advanced Liquid-Metal Reactors.

Briefers: George Wicks (Westinghouse Savannah River); Ed Moore (Westinghouse Savannah River); Paul Cunningham (Los Alamos National Laboratory); Victor Alessi (Director, DOE Office of Arms Control and Nonproliferation); James Lovett, International Atomic Energy Agency (retired); Lawrence Scheinman (Cornell University); Sol Rosen (DOE, Office of Nuclear Energy); Melvin Buckner (Westinghouse Savannah River); Rulon Linford (Los Alamos National Laboratory); Edward Arthur (Los Alamos National Laboratory);

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Chris Hamilton (General Atomics); William Hannum (Argonne National Laboratory); Marion Thompson (General Electric); others.

January 25, 1993: Lawrence Livermore National Laboratory (LLNL)

Utility of Reactor-Grade Plutonium in Nuclear Explosives; Separating Plutonium from Spent Fuel; Radiation Exposure from Plutonium Handling; Detection of Nuclear Weapons; Reports of Illicit Sales of Fissile Material.

Briefers: William Sutcliffe; Lou Eccles; Carl Walter; Harry Vantine; Leonard Gray; Melvin Coops; Guy Armantrout; Bill Nelson; Jack Robbins; Tom Smith; John Sherohman; others. All briefers LLNL.

February 17, 1993: CISAC Meeting, Victor Mikhailov

Current Russian Policy on Weapons Dismantlement, Plutonium Storage, and Plutonium Disposition.

Discussant: Victor Mikhailov, Minister of Atomic Energy, Russian Federation.

March 17, 1993: DOE Headquarters, Washington D.C.

Plutonium Storage Forms; Potential Transparency Measures for Warhead Dismantlement, Fissile Material Production, and the HEU (Highly Enriched Uranium) Purchase; Intelligence Collection for Detecting Fissile Materials Production; Estimates of Russian Fissile Materials Production.

Briefers: John Wacker (Pacific Northwest Laboratories); Andrew Bieniawski (DOE, Office of Arms Control and Nonproliferation); Max Koontz (DOE, Office of Arms Control and Nonproliferation); James Dewar (DOE, Office of Foreign Intelligence); David Dye (LLNL); others.

March 31-April 1, 1993: Los Alamos National Laboratory (LANL)

Plutonium Storage Forms; Pit Disassembly and Processing; Russian Fissile Material Storage Facility; Accelerator-Based Conversion; Tour of Plutonium Processing Facilities.

Briefers: Paul Cunningham (LANL); Kirk Ellard (LANL); Rulon Linford (LANL); Steve Guidice (Manager for Operations and Weapons, DOE Albuquerque Operations Office); Delbert Harbur (LANL); others.

April 1, 1993: Savannah River Site

Plutonium Processing and Storage; Vitrification Options; Tour of Plutonium Storage, Processing, and Reprocessing Facilities; Tour of Defense Waste Processing Facility.

Briefers: James Angelos; Malvyn McKibben; Vern Fernandez; Hank Elder; others. All briefers Westinghouse Savannah River.

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April 5, 1993: Pantex Plant

Weapons Disassembly; Plutonium Storage; Future Plans; Tours of Disassembly and Storage Areas

Briefers: Gerald W. Johnson (Acting Area Manager, DOE, Amarillo); Steve Guidice (DOE, Albuquerque Operations Office); Richard Loghry (General Manager, Mason and Hanger-Silas Mason).

April 22, 1993: CISAC Meeting, Washington, D.C.

Criteria for Plutonium Disposition; Option of Substituting Weapons Plutonium in Planned Civilian Plutonium Programs.

Briefers: Thomas Cochran; Christopher Paine. Both briefers Natural Resources Defense Council.

May 17-21, 1993: Moscow

(Listed by organization, not topic; a variety of topics was discussed at each meeting.)

Ministry of Atomic Energy: Deputy Minister Nikolai Yegorov; Mikhail Ryzhov (Chairman, Committee on External Relations); Boris Gorobets (Director, Chief Administration of Nuclear Warhead Production (includes assembly and disassembly)); Georgi Tsyrkov (Director, Chief Administration of Nuclear Warhead Design and Testing); Victor M. Murogov (Director, Obninsk Institute of Physics and Power Engineering); Evgeniy G. Kudriavtsev (Research and Production Nuclear-Chemical Administration (enrichment and reprocessing)); Fedor G. Reshetnikov (Bochvar Institute of Inorganic Materials); others.

Ministry of Defense: General Sergei Zelentsov (retired, former commander, 12th Main Directorate (in charge of nuclear weapons)); Colonel-General Vitali Yakovlev (Deputy Commander, 12th Main Directorate).

Ministry of Foreign Affairs: Deputy Minister Grigority Berdennikov; Victor Slipchenko (Deputy Director, Disarmament and Military Technologies Control); Sergei Kisliak; Victor Mizin.

GOSATOMNADZOR: Chairman Yuri Vishnevsky; First Deputy Alexander Gutzalov; Deputy Chairman Yuri Zoubkov; Alexander Dmitriev (Director, Department of Nuclear and Radiation Safety of Fuel Cycle Installations); Nikolai Bisovka (Director, Department of Nuclear and Radiation Safety of Defense Installations); Vadim Petrov (Director, Scientific Committee); Vladimir Formichev (Director, Nuclear Weapons Department); Yuri Rogozhin (Director, International Relations); others.

Russian Academy of Sciences: President Yuri Osipov; Vice President Nikolay P. Laverov; Vice President Rem V. Petrov; Academician Yuri Ossipian; others.

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Supreme Soviet: Lieutenant-General (retired) Alexander I. Voronin (member, Committee on State Defense and Security); Anatoli D. Novikov (committee staff); Vadim G. Osinin (committee staff).

Kurchatov Institute: Director Evgeniy P. Velikhov; Deputy Director Nikolai N. Ponomarev-Stepnoi; Vladimir N. Sukhoruchkin; Vladimir Shmelev; Alexander Kalugin; others.

Nuclear Safety Institute: Director Leonid A. Bolshov; Deputy Director (International Relations) Vjatcheslav N. Lyssakov; others.

Research and Development Institute of Power Engineering (NIKIET): Deputy Director Victor V. Orlov; others.

Institute of USA and Canada Studies: Deputy Director Sergei Rogov; others.

Association for Nonproliferation: Director Andrei V. Zagorski; Deputy Director Vladimir Shmelev.

U.S. Embassy: Science Counselor Robert Clarke; Karen Malzahn.

International Science and Technology Center: Director Glenn Schweitzer; Vladimir Kryuchenkov (Department Leader, Experimental Physics, Chelyabinsk-70); others.

June 8, 1993: Meeting with Intelligence Community, Washington D.C.

Russian Plutonium Production, Stockpiles, and Processing; Status of Accounting and Security for Weapons and Fissile Materials

Briefers: Lawrence Gershwin (National Intelligence Officer for Strategic Programs); others.

July 2, 1993: DOE Headquarters, Washington D.C.

DOE Plutonium Storage Plans.

Briefers: Howard Canter (DOE Deputy Assistant Secretary for Weapons Complex Reconfiguration); others.

July 15, 1993: DOE Headquarters, Washington D.C.

DOE Plutonium Stockpile, Quantities and Forms.

Briefer: Louis R. Willett (DOE, Deputy Director, Office of Weapons and Materials Planning).

Committee and panel meetings that did not include briefings, briefingsfor the Panel on Reactor-Related Options, and additional briefings for individual CISAC members and staff are not included.

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Appendix B

Profiles of Civilian Plutonium Programs

This appendix contains brief descriptions of the current status of the civilian plutonium programs of six major nations—Germany, France, Great Britain, Japan, Russia, and the United States.[1] Programs in several of these countries are changing rapidly, as policies face legal and political challenges. The information contained here reflects the situation as it stood in the fall of 1993.

GREAT BRITAIN

Great Britain has 37 operating nuclear power reactors that generate 23 percent of its electricity (12,066 megawatts-electric; MWe). One reactor, which will provide an additional 1,188 MWe, is under construction.[2]

***Basic Policy and Spent Fuel Management Plans*.** Great Britain has a mixed strategy for managing the spent fuel from its power reactors,[3] and no

[1] Much of the basic information about each nation's programs and plans is drawn from David Albright, Frans Berkhout, and William Walker, *World Inventory of Plutonium and Highly Enriched Uranium 1992* (London: Oxford University Press for SIPRI, 1993). Recent developments are generally drawn from nuclear industry press reports; these are noted separately. In addition, Frans Berkhout provided current information on some aspects of various national programs, particularly regarding spent fuel management policies.

[2] Information on electricity generation in each country comes from "1992 World Energy Production and Consumption," *NUKEM Report*, October 1993, p. 50-51.

[3] All spent fuel from British MAGNOX reactors is being reprocessed, some spent fuel from its advanced graphite reactors is reprocessed, and no decision has been made on what will be done with spent fuel from the pressurized water reactor at Sellafield.

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overall long-term plan beyond storage. Research and development work for a deep geologic repository to store high-level waste (HLW) is under way at Sellafield. HLW is currently stored in facilities at Sellafield and at Dounreay, site of the British prototype fast reactor.

Britain also has agreements to reprocess spent fuel for other nations. In this case, the policy is to return vitrified HLW to the producing country within approximately one year.[4]

Reprocessing. Britain has engaged in reprocessing activity since the early 1950s, both for its weapons program and because the fuel elements from its MAGNOX power reactors were difficult to store for an extended period. Purely civilian plutonium reprocessing began in 1964. Currently, MAGNOX fuel is reprocessed at the B205 facility at Windscale/Sellafield, which has a design capacity of 1,500 metric tons of heavy metal each year (MTHM/yr).

As of late 1993, the major issue was whether the large new reprocessing facility, THORP (Thermal Oxide Reprocessing Plant), would open. An intense campaign by environmentalists had significantly delayed the opening, but the British government was expected to give permission by the end of 1993. This would permit the process of starting up the facility to begin in early 1994.

If THORP does open and if it operates as planned, by the end of the decade it would be producing about 5.5 tons of plutonium each year. THORP's owners, British Nuclear Fuels Limited (BNFL), have contracts for work through the rest of the decade. There is some question, however, tied to other countries' nuclear policies, whether BNFL can secure contracts for reprocessing beyond 2002. In its first 10 years of operation, an estimated two-thirds of THORP's work would be reprocessing spent fuel for other countries. Most of its foreign work would be for the Japanese, but the facility also has contracts from Germany, Italy, the Netherlands, Spain, and Switzerland. A German or Japanese decision to slow or abandon reprocessing could seriously affect THORP's profitability.

Fuel Fabrication and Use. A small (8-MTHM/yr) demonstration mixed-oxide (MOX) fuel fabrication plant built by BNFL is scheduled to open in 1994. BNFL has also pushed for construction of a MOX fabrication plant that would open in the late 1990s, possibly through a technology transfer agreement with the German corporation Siemens for the same design and 120-MTHM/yr capacity as the stalled facility in Hanau, Germany.[5] At the moment, however, little has moved beyond preliminary discussions. British power reactors currently do not use MOX fuel, and at present there is no plan to recycle plutonium.

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[4] Frans Berkhout, "Fuel Reprocessing at THORP: Profitability and Public Liabilities," Greenpeace, 1992, p. 13.

[5] Mark Hibbs, "BNFL to Decide This Year Whether to Build MOX Facility," *Nuclear Fuel*, September 14, 1992, p. 10.

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With the British fast breeder program canceled, plutonium is thus accumulating.[6]

GERMANY

As of the end of 1992, Germany had 21 nuclear power reactors in operation, which provided 30 percent of its electricity. No additional reactors were under construction.

Basic Policy and Spent Fuel Management Plans. Germany's civilian nuclear programs are governed by its Atomic Law, which mandates reprocessing and recycle as the only spent fuel management approach when these are "justified on technical and economic grounds."[7] This has long been regarded as prohibiting long-term storage of HLW as a disposition option. Political opposition to reprocessing and recycling (see below) had led the German parliament to consider amending the Atomic Law to permit extended spent fuel storage. No revision appears likely until after the federal elections in 1994, however, as this proposed change has become part of a larger review of energy policy.

A report released in September 1993 by the Bundesrechnungshof (BRH), the federal accounting office, has further complicated the picture. The report concluded that the high costs of reprocessing meant that the process "is no longer qualified" as a spent fuel management option. "Our investigation led to the conclusion—which was not challenged by federal ministries—that reprocessing is at least twice as expensive as direct disposal of spent fuel."[8] As of the time of this report, the German government had not accepted the BRH report and maintained that reprocessing was still the only legal disposition policy under the Atomic Act.

Reprocessing. Germany had a small, pilot reprocessing capability that operated from 1971 to 1990, and the government had made plans for a larger commercial operation. Those plans were abandoned in 1989 in a joint decision with the utility planning to construct the plant. This means that Germany must rely on other countries to reprocess the spent fuel from its nuclear power plants. Germany has extensive reprocessing contracts with France for current work and also has major contracts with Great Britain for future reprocessing at THORP. These contracts all carry significant penalty clauses for cancellation.

Fuel Fabrication and Use. Current German policy calls for recycling all the plutonium separated in reprocessing as fuel for its reactors, and all German

[6] The British government has withdrawn its financial support from the Dounreay Prototype Fast Reactor (PFR), and it is expected to shut down in 1994.

[7] Title 9 of the Federal Atomic Act, quoted in Mark Hibbs, "No Justification for Reprocessing, German Accounting Office Concludes," *Nuclear Fuel*, September 13, 1993, p. 7.

[8] The quotes from the report are found in Hibbs, ibid., p. 7.

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reactors are to be able to burn MOX.[9] Ten German reactors are currently licensed to use MOX, although only seven have done so to date, and another eight are in various stages of the licensing process. Some German plutonium is being fabricated into MOX at the 35-MTHM/yr facility in Belgium run by a French-Belgian joint venture.

Local- and state-level opposition to nuclear power is very strong in some parts of Germany, however. The Green-Social Democratic Party government that came into office in the state of Hesse in 1991 has shut off all of Germany's MOX fuel fabrication capabilities, which were located in Hanau. A 35-MTHM/yr facility was closed in 1991 for safety reasons and has not been permitted to reopen. More importantly, the state government succeeded in halting construction of a 120-MTHM/yr facility that was more than 90 percent completed. The court battles have gone on for more than 18 months, and so far the Hesse government has prevailed.[10] Nuclear industry press reports indicate that the German utilities involved in the Hanau facility have told the prime contractor, Siemens, that they would not continue to support the maintenance of the facility much after the end of 1993 without a political agreement to complete the facility and allow it to operate.[11] At present, the long-term prospects for MOX fabrication in Germany are very uncertain.

With MOX production stalled, separated plutonium from German spent fuel is accumulating in France after reprocessing. France is continuing to separate plutonium from German fuel under existing contracts, but in line with a general European policy agreement in 1984, France will not return the separated plutonium unless the capability exists to process it immediately into reactor fuel and load it into reactors. At present, about 6 tons of separated German plutonium is in storage at La Hague. Under existing contracts, another 25 tons of plutonium is scheduled to be separated by the end of the decade.[12]

FRANCE

France has 56 nuclear power reactors that supply almost 75 percent of its electricity. Another 5 reactors are under construction.

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[9] Germany has a long history of interest in MOX. The first MOX research and development program began in the mid-1960s.

[10] A ruling in the summer of 1993, for example, invalidated all the preliminary operating licenses that had been granted at various stages of construction on the grounds that a full safety analysis should have been completed first. If the ruling stands, the manufacturer, Siemens, must begin the entire licensing process over, which could take several years. Mark Hibbs, "German MOX Plant Loses Licenses; Utility Commitment on the Line," *Nuclear Fuel*, August 2, 1993.

[11] *Ibid.* Other reports indicate that German utilities have begun talking about package deals for reprocessing and MOX fabrication with the French company COGEMA. BNFL is also reported to have made a proposal to supply Germany's MOX needs. Mark Hibbs and Ann MacLachlan, "German Utilities Negotiating to Shift MOX Fabrication to France, Belgium," *Nuclear Fuel*, September 27, 1993, p. 3.

[12] Mark Hibbs and Ann MacLachlan, "Pu Storage at La Hague Will Cost German Utilities Over $16 Million," *Nuclear Fuel*, June 21, 1993, p. 4.

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Basic Policy and Spent Fuel Management Plans. Of all the countries discussed here, France has the strongest government commitment to nuclear power and a closed fuel cycle. France plans to reprocess all its spent fuel. It will vitrify its HLW and is conducting research on a geologic repository. In the meantime, it is constructing interim HLW storage depots at its reprocessing facilities. These will handle waste from French domestic power programs, as well as from reprocessed foreign spent fuel. The latter is to be returned to the country of origin for eventual disposition.

Reprocessing. France is currently the world's major provider of reprocessing services, with Germany and Japan as its primary customers. A new facility, UP3, opened in 1990, is devoted completely to foreign work. An older facility, UP2, continues to handle some foreign reprocessing as well, and construction to expand its capacity from 400 to 800 MTHM/yr is scheduled to be completed in 1994. The French reprocessing program might suffer if either Germany or Japan slowed or gave up reprocessing.[13]

Fuel Fabrication and Use. France has a small (15-MTHM/yr) MOX fabrication facility that supplies a limited amount of fuel to its light-water reactors (LWRs). As already noted, France is a partner with Belgium in the world's only operating commercial MOX fabrication facility, located in Dessel, Belgium. The plant has a capacity of approximately 35 MTHM of MOX annually, with most of its production going to French reactors.[14] Sixteen French reactors are licensed to burn MOX, and five are currently doing so. The rest of the MOX produced at Dessel goes to Swiss, German, and Belgian utilities. France and Belgium also have a joint marketing organization, COMMOX, to sell fuel fabrication services. France is constructing a large MOX fuel plant with a 120-MTHM/yr capacity, which is scheduled to open in 1995-1996.[15]

Fast Reactors. The world's only large-scale commercial fast reactor, Superphenix, is located in France. Technical problems plagued Superphenix from the beginning, and it operated for less than five years (1986-1990). The French government has begun the administrative process necessary to obtain the operating license to restart Superphenix. No decision had emerged by fall 1993, but the outcome was expected to be permission for Superphenix to resume operations. Industry press reports suggest that the prototype breeder reactor, Phenix, which has been shut down for three years because of concerns

[13] French nuclear energy officials thus reacted strongly to reports that Germany might rethink its commitment to reprocessing, stressing the heavy financial penalties that a default would impose. Ann MacLachlan and Pearl Marshall, "BNFL, COGEMA Heads: Germans Say Reprocessing Contracts Will Stay," *Nuclear Fuel*, December 10, 1992, p. 3.

[14] There are plans to build a second facility at the same location that would double capacity to 70 MTHM/yr.

[15] As mentioned earlier, in the wake of Germany's problems with its Hanau facility, nuclear industry press reports indicate that German utilities have begun talking to the French-Belgian company about supplying their MOX needs. Mark Hibbs and Ann MacLachlan, "German Utilities Negotiating to Shift MOX Fabrication to France, Belgium," *Nuclear Fuel*, September 27, 1993, p. 3.

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about its cooling system, might be given a license to undertake an operating cycle in 1994.[16]

JAPAN

Japan currently has 44 nuclear power reactors that supply 28 percent of its electricity; another 9 are under construction.

Basic Policy and Spent Fuel Management Plans. Given its strong concern for energy independence, Japan plans to develop a complete plutonium fuel cycle. It has explicitly ruled out disposal of spent fuel in a geologic repository as a disposition option, in favor of reprocessing. Plans call for the vitrification of HLW from reprocessing, which will then be stored for 30-50 years prior to final disposal. A demonstration vitrification facility began testing operations in May 1992.

Reprocessing. Japan has a reprocessing facility at Tokai-mura with a design capacity of slightly more than 200 MTHM/yr, but it has never performed up to expectations. Thus, at present, Japan relies on other countries for reprocessing services; for example, the French are reprocessing U.S.-origin low-enriched uranium (LEU) spent fuel from Japanese power plants.[17] This practice has proved to be controversial. The return shipment of 1.7 tons of reprocessed plutonium from France in the fall of 1992 caused a storm of protest.[18] The Japanese government was reported to be deeply concerned by the international reaction to its policies. This led to the first indications that Japan might be beginning to reconsider some aspects of commitment to a plutonium economy. Some analysts believe that the recent change in Japan's government from the long-dominant Liberal Democratic Party may further encourage debate.

Japan plans to build an 800-MTHM/yr reprocessing facility at Rokkasho-mura that is to come on-line after 2000. This facility is intended only for domestic use; at present Japan has no plans to enter the international fuel services market.

Fuel Fabrication and Use. Japan has a small MOX fabrication facility that provides fuel for its experimental and prototype reactors. There are also tentative plans to build a 100-MTHM/yr MOX plant at Rokkasho-mura. Until that is completed, Japan will depend on purchasing plutonium fuel fabrication services in Europe. Japan is in the process of licensing a number of its reactors to handle MOX fuel, but none is as yet approved to do so.

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[16] Ann MacLachlan, "DSIM Leaves CEA Optimistic Phenix Could Operate in 1994," *Nucleonics Week*, September 9, 1993, p. 3.

[17] In addition to the reprocessing services provided by France, the spent fuel from Japan's single MAGNOX reactor is reprocessed by the British at Sellafield.

[18] Japanese officials have stated that future shipments will be in the form of MOX rather than pure plutonium oxide, but this may not assuage the opponents whose concerns are based on both environmental and nonproliferation risks of transporting any form of plutonium.

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Fast Reactors. Japan is investing in all the elements of the plutonium fuel cycle. A prototype "Monju" fast reactor is currently scheduled to begin operation in the spring of 1994, and two other demonstration breeder reactors are planned in the next decade.

RUSSIA

Russia has 28 nuclear power reactors that supply 12 percent of its electricity. Another 18 are under construction, but the current economic crisis makes it uncertain how many, if any, will be completed.

Basic Policy and Spent Fuel Management Plans. The Soviet, and now Russian, approach to nuclear power is based on a closed fuel cycle, including reporcessing of spent fuel and a planned eventual shift to breeder reactors.[19] The current Russian plan is to reprocess the spent fuel from all of its reactors except the RBMKs, whose fuel includes a lower percentage of plutonium, thus worsening the economics of recovering the plutonium. RBMK spent fuel is currently being stored pending decisions on long-term management. The disintegration of the former Soviet Union and the resulting economic and political upheavals have cast considerable doubt on whether and when these ambitious plutonium plans will be brought to fruition.

Any discussion of the former Soviet/Russian program is complicated by the fact that, unlike the United States, military and civilian efforts are not segregated. Nevertheless, this discussion focuses primarily on civilian activities.

Reprocessing. Three main reprocessing sites exist on Russian territory, at Chelyabinsk, Tomsk, and Krasnoyarsk. The Chelyabinsk facility, known as the Mayak Chemical Combine, includes the RT-1 reprocessing plant. This plant has a design capacity of 400 MTHM/yr, although throughput has historically averaged roughly half that. Recently it has declined further, to approximately 120 MTHM/yr, partly because of disagreements between Russia and other states whose fuel was to have been reprocessed there under agreements with the Soviet Union. This plant was previously used to separate weapons plutonium from plutonium production reactors, but it is now used to separate reactor-grade plutonium from VVER-440 and breeder reactor fuel, as well as fuel from naval and research reactors.

There are 23 VVER-440 reactors in all, of which only 8 are in the former Soviet Union, with the remainder in Eastern Europe and Finland. The current

[19] Useful sources on Russian plutonium facilities and plans include, among others, Thomas B. Cochran and Robert Standish Norris, *Russian/SovietNuclear Warhead Production* (Washington, D.C.: Natural Resources Defense Council, September 8, 1993); D.J. Bradley, "Radioactive Waste Management in the Former USSR," Volume III, Pacific Northwest Laboratory, Office of National Security Technology, June 1992; Yu. K. Bibilashvili and F.G. Reshetnikov, "Russia's Nuclear Fuel Cycle: An Industrial Perspective," *IAEA Bulletin*, Vol. 35, no. 3, 1993; and E.G. Kudriatsev, "Russian Prospects for Plutonium Accumulation and Utilization," unpublished paper, presented to an International Atomic Energy Agency meeting on problems of separated plutonium, April 1993.

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Russian debate over whether to accept nuclear waste from other countries is thus a significant issue in its relations with these states. Spent fuel storage space in several of these countries (including Ukraine) is beginning to run out. Because no plutonium is being recycled into light-water reactors, and large-scale breeder reactors have not yet been built, some 26 tons of excess separated plutonium have built up at the Mayak facility. At the current rate of reprocessing, roughly one additional ton is added each year.

The Tomsk reprocessing plant, used to separate weapons plutonium still being produced in three production reactors, was shut down on April 6, 1993, as a result of an explosion in a tank used in the PUREX reprocessing process, but it had restarted by late summer of that year. At the Krasnoyarsk facility, there is another (underground) reprocessing plant used to separate weapons plutonium. There is also a large, partially completed, civilian reprocessing plant known as RT-2, designed to reprocess VVER-1000 spent fuel, which was to have had a capacity of 1,500 MTHM/yr. Construction at RT-2 has been stopped for several years due to lack of funds, however, and it is not clear when, if ever, it will resume. Russia has been discussing the possibility of obtaining funds to complete this plant in exchange for reprocessing spent fuel with several countries, including Ukraine and South Korea.

Fuel Fabrication and Use. Russia has several pilot-scale plutonium fuel fabrication facilities. The main ones are at the Mayak facility (which employs a pelletized approach to MOX fabrication similar to that used in other countries) and in Dimitrovgrad (where a vibrocompaction approach involving no pellets has been developed). The BN-350 and BN-600 fast reactors run primarily on uranium fuel, but have conducted tests with plutonium fuel assemblies, both weapons-grade and reactor-grade.

Construction of a large MOX fabrication facility known as "Complex-300," with a planned capacity of about 120 MTHM/yr, started at Chelyabinsk in 1985 and is now estimated to be roughly 50 percent complete.[20] Construction has been halted for several years, and hundreds of millions of dollars could be required to complete the facility. As with RT-2, it is not clear when, if ever, construction of this facility will resume. The facility would produce fuel for the four planned BN-800 fast reactors, whose future is also in doubt. A MOX fabrication plant at Krasnoyarsk with a capacity of roughly 200 MTHM/yr, designed to produce fuel for VVER-1000 reactors, is in the planning stages, but even if all goes well it will not be available until well after the turn of the century.

Fast Reactors. Two fast reactors, the BN-600 in Russia and the BN-350 in Kazakhstan, have burned plutonium fuel on an experimental basis, although as mentioned above they have operated primarily on highly enriched uranium (HEU) fuels. The Ministry of Atomic Energy (MINATOM) remains committed to building three to four large BN-800 breeder reactors. Construction of the first

[20] Cochran and Norris, op. cit., p. 60.

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reactor, however, has been stopped for several years, and it is not clear when construction of such reactors will resume. Although some MINATOM officials continue to estimate that the first of these reactors will begin operation as soon as 1997, senior MINATOM official Boris Nikipelov recently estimated that it would be 10-15 years before the first of these reactors is completed, an estimate others continue to find optimistic.[21]

UNITED STATES

The United States has 109 operating nuclear power reactors, which supply 22 percent of the nation's electricity.

Basic Policy and Spent Fuel Management Plans. The United States has a once-through fuel cycle with disposal rather than reprocessing of the spent fuel from its nuclear reactors. President Carter decided against a civilian plutonium fuel cycle in the 1970s based on concerns over proliferation, economics, and environmental consequences.[22] A major licensing effort for use of plutonium fuels in U.S. reactors then in progress was terminated. Later, Congress terminated the Clinch River breeder reactor program as well, although research on advanced fast reactors has continued.

Under Presidents Reagan and Bush, there were no prohibitions on domestic reprocessing, but since plutonium fuel use was not economically competitive with LEU fuels, no civilian reprocessing was undertaken. Thus, 70,000 tons of spent fuel from U.S. LWRs, along with vitrified HLW from past military and commercial reprocessing, are to be disposed of in the Yucca Mountain geologic depository, if and when that facility is approved.

Reprocessing. The military plutonium reprocessing facilities at Hanford, Washington and at Savannah River, South Carolina have largely closed down, although there is now discussion of reprocessing some materials that may be difficult to store for prolonged periods. The commercial reprocessing facility at West Valley, New York has been closed for well over a decade.

Fuel Fabrication and Use. No operating plutonium fuel fabrication facility exists in the United States. At the Hanford site, there is a partly completed MOX fabrication facility designed to provide fuel for experimental fast reactors. It could be modified and completed to produce some 50 MTHM/yr of light-water reactor fuel. No U.S. power reactors are currently licensed to burn MOX fuel, although with varying degrees of modification all U.S. LWRs could burn a one-third core. In addition, three currently operating and one partially completed System-80 LWRs could burn a full core of MOX fuel.

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[21] See Mark Hibbs, "Waste Disposal Top Priority for Back End, Nikipelov Says," *Nuclear Fuel*, July 19, 1993.

[22] *Presidential Documents—Jimmy Carter*, Vol. 13, no. 15, April 18, 1977.

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Fast Reactors. The United States has two small experimental fast reactors. The Fast Flux Test Facility (FFTF) is on standby mode and would take more than a year to restart. At present, there are no plans to do so. The smaller Experimental Breeder Reactor II (EBR-II) was to be phased out under the Fiscal Year 1994 budget proposed by the Clinton administration, but Congress has voted to keep it running, and debate over its future continues. Research on fast reactors continues in the Integral Fast Reactor (IFR) program, headed by the Argonne National Laboratory; the chief corporate sponsor is General Electric. The research is currently focusing on recycling plutonium and other actinides as a waste-management approach, but future funding is uncertain.

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Appendix C

Nonreactor, Nonrepository Disposal of Excess Weapons Plutonium: Technical Issues

INTRODUCTION

Chapter 6 describes a variety of options for dealing with long-term disposition of weapons plutonium. The options involving nuclear reactors, accelerator-driven subcritical assemblies, and reactor wastes are described in more detail in the report of the Panel on Reactor-Related Options for the Disposition of Excess Weapons Plutonium.[1] This appendix offers additional detail on the disposal options not covered in that report, including:

- disposal in deep boreholes;
- sub-seabed disposal;
- ocean dilution;
- space disposal; and
- underground nuclear explosions.

Consistent with the discussion in Chapter 6, options should:

[1] *Management and Disposition of Excess Weapons Plutonium: Reportof the Panel on Reactor-Related Options* (Washington, D.C.: National Academy Press, 1994).

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1. minimize the time during which the plutonium is stored in forms readily usable in weapons;
2. preserve material safeguards and security during the disposition process, seeking to maintain the same high standards of security and accounting applied to stored nuclear weapons;
3. result in a form from which the plutonium would be as difficult to recover for weapons use as the larger and growing quantity of plutonium in commercial spent fuel; and
4. meet high standards of protection for public and worker health and for the environment. This criterion must include not only expected situations but possible failures (particularly during the disposal process), and not only safety but the extent to which that safety is demonstrable to the public.

In addition, this appendix examines the costs of the various options, issues such as public and institutional acceptance, and possible conflicts with existing agreements and policies.

Several of the disposal options that might be pursued for disposition of excess weapons plutonium have also been considered for disposal of spent fuel or high-level waste (HLW), for which the international consensus today favors burial in mined geologic repositories, rather than any of the disposal options outlined in this appendix. There are a number of important differences, however, between weapons-grade plutonium and spent fuel or HLW. These include:

- *Heat*. The heat output of weapons plutonium is roughly 3 watts per kilogram, or 30 watts for a package containing 10 kilograms of plutonium. A comparable disposal package of 10-year old spent fuel or HLW typically gives off 1,000-2,000 watts of heat.
- *Radioactivity*. The gamma radiation from a typical package of weapons plutonium at 1 meter would mount to only thousandths of a rem (roentgen-equivalent-man) per hour, while for spent fuel assemblies or vitrified logs of HLW, the equivalent figure is thousands of rems per hour (for the first few decades after these products are produced).
- *Toxicity*. Weapons plutonium, spent fuel, and HLW are all highly toxic, primarily because of their radioactivity. The alpha radiation from plutonium is particularly damaging if the small particles are inhaled and lodge in the lungs. Environment and health risks from all of these materials must be carefully considered over very long times in evaluating disposal options.
- *Mass and Volume*. The nominal stock of excess weapons plutonium is 50 tons each for the United States and Russia, which could in principle be stored in a single large warehouse. The global stock of spent fuel by the year 2000 will amount to more than 150,000 tons (containing over 1,400 tons of plutonium), occupying a vastly larger volume. Thus some options that might be prohibitively costly for spent fuel might not be so for excess weapons plutonium.

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- *Perceived Value and Security Risk*. HLW has virtually no value to anyone; hence, it is extremely unlikely that anyone would seek to recover the material, except perhaps to monitor the disposal mechanism or to correct a perceived failure of that mechanism. By contrast, weapons plutonium might have significant economic value as a fuel decades from now, and even several kilograms of weapons plutonium could be extremely valuable to a proliferator for use in nuclear weapons. For a particular disposal approach to meet the "spent fuel standard" outlined in Chapter 6, it must be as difficult (measured in likely cost, time, and availability of the needed technologies) to retrieve the plutonium for use in weapons as it would be to separate a similar amount of plutonium in spent fuel for the same purpose.

DISPOSAL IN DEEP BOREHOLES

Description

Disposal in deep boreholes has been considered in several countries for spent fuel or HLW (generally as a backup to the currently preferred approach of disposal in mined geologic repositories nearer the surface), and this is a possible approach for plutonium disposal as well. Studies in Denmark, the United States, and Sweden have examined the borehole approach in some detail.[2] The approach appears technically feasible, though a substantial period of additional development would be required to answer outstanding questions and provide information for licensing.

For example, wastes might be emplaced in the lower 2,000 meters of a hole drilled to a depth of 4,000 meters, with a diameter of 1 meter. Rather than simply placing plutonium pits in canisters in such a hole, some processing before emplacement would be required, to eliminate void space and to prevent the possible development of conditions in which the plutonium could sustain a nuclear chain reaction, producing heat and fission products in the hole—so-called "criticality."[3] Nevertheless, even if the plutonium itself were only 10 percent of the weight of the final product (and an even smaller fraction of its volume), it

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[2] For a recent summary discussion, see J. Swahn, *The Long-Term NuclearExplosives Predicament: The Final Disposal of Militarily Usable FissileMaterial in Nuclear Waste from Nuclear Power and the Eliminationof Nuclear Weapons*, ISBN 91-7032-689-4 (Goteborg, 1992). A Swedish summary report is particularly useful: Svensk Karnbranslehantering AB (Swedish Nuclear Fuel and Waste Management Co.), *Storage of NuclearWaste in Very Deep Boreholes: Feasibility Study and Assessment ofEconomic Potential*, Technical Report 89-39 (in English), December 1989. Earlier work is reported, for example, in Woodward-Clyde Consultants, *Very Deep Hole Systems Engineering Studies*, ONWI-226 (San Francisco: Woodward-Clyde Consultants, April 1981). The baseline concept in the latter is a 20,000-foot (6-kilometer) borehole, in contrast to an even more challenging initial proposal of 10-kilometer depth.

[3] For example, the plutonium might be vitrified in a borosilicate glass before emplacement, as described in Chapter 6 for placement in a mined repository; in this case, vitrification could be without HLW, since the difficulty of access to the deep borehole would provide the primary barrier to retrieval of the plutonium.

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would be possible in principle to place the nominal 50-metric-ton stock of excess weapons plutonium in a single borehole.

Boreholes have been drilled to depths between 1,500 and 6,000 meters in the United States, Germany, the former Soviet Union, Italy, and Sweden. Thus the feasibility of drilling holes to appropriate depths can be considered demonstrated, although emplacing large quantities of material at depth would involve some additional engineering challenges. A deep borehole for disposal of either HLW or weapons plutonium would have to provide a substantial *volume* at depth, in contrast with the usual deep hole for exploration or for the production of oil or gas.

For example, a detailed Swedish study on HLW disposal in deep holes focuses on a "preferred option" that would involve a hole 80 centimeters in diameter at depth, into which would be placed canisters with a length of 4.4 meters and a diameter of 50 centimeters, centered in the hole.[4] Each canister would be separated from the next by sealing plugs of compressed bentonite clay. After the "deployment zone" was filled, an additional long length of bentonite clay would be used to seal the hole. For the depth range of 250-500 meters, asphalt would be emplaced in the hole, and for the top 250 meters, a high-density concrete would be used to provide a cap.

The hole would be drilled with normal drilling equipment, with the upper portions having a wider diameter than the actual deployment zone. The upper portion of the hole in the Swedish concept would have a casing with an internal diameter of 100 centimeters, while the lower portion would have a "liner" throughout the deployment zone with an internal diameter of 60 centimeters (2 feet) to allow the deployment of the 50-centimeter-diameter canisters. The upper casing might be pulled after deployment. As the Swedish report points out, the United States took a similar approach in the drilling of a deep hole on Amchitka Island, Alaska, in 1969. The casing emplaced there was 1,860 meters long, with a diameter of 137.5 centimeters, a weight of 1,820 tons, and a wall thickness of 6.4 centimeters. Such a hole could be prepared in less than a year, and filled and sealed in another year or so.

The "liner" for the hole envisioned in the Swedish study—used to keep the borehole open for deployment of the canisters—would be quite different from anything used in normal drilling practice today, in that a substantial fraction of it would be holes open to the surrounding rock, so that the sealing clay could readily extrude through the liner to make good contact with the rock wall of the hole. The clay would provide support for the hole wall and would help seal any cracks or fissures.

Crystalline rock at great depth is under substantial stress. Because of the uneven grain of the rock and the slow strain of the earth's crust, the horizontal stress is not uniform—the rock is being pulled in some directions more than others. Typically, the maximum horizontal stress may be 1.5 times the vertical

[4] See Svensk Karnbranslehantering AB, op. cit.

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stress ("lithostatic pressure"), whereas the horizontal stress at right angles to the maximum may be 0.5 times the vertical stress.

Because of the uneven stress on the rock at depth, when a hole is drilled into it the rock tends to be pulled in such a way that the hole becomes elliptical and usually develops "ears"—extensions of the hole at the ends of the ellipse. To minimize this "spalling" problem, the driller must choose an optimum density for the drilling fluid. Drilling with water would mean that the pressure in the rock outside the borehole would be much higher than the support pressure of the water on the wall of the borehole (at the depths of interest), which could lead to the borehole collapsing inward. Using very dense mud can lead to the opposite problem, which can cause the surrounding rock to crack. Even the optimum mud density can do no more than to provide a pressure at depth that is the same in all directions; some cracking and elliptical growth of the cross section of the hole would still result. This must be taken into account, both as it affects deployment of the HLW or plutonium in the hole and as it affects the effectiveness of containment in the hole after the canister disintegrates in time.

Environmental Impact

Would the borehole reliably prevent the plutonium from being released into the environment at harmful concentrations? Although boreholes have not received anything like the technical scrutiny that has been applied to mined repositories, the great depth of the hole and the very low permeability of crystalline rock (granite) suggest that the risks of radioactive releases from such holes might be even lower than those from mined repositories. The small area of disturbed material, the long path to the surface, and the possibility of plugging many hundreds of meters of hole with diffusion and convection barriers may make this concept effective. Furthermore, the relatively small area exposed means that the materials will be exposed to only a small water flow, and poorly soluble materials such as plutonium will dissolve quite slowly. The main questions are how the plutonium might be conveyed to the surface once emplaced and the potential for accident during emplacement.

Crystalline rock at depth has very low porosity and hydraulic conductivity (the ability of water to move through the rock). This means that movement of the plutonium through uncracked rock would be extremely slow, even if water that might be in the borehole ultimately contacted and became saturated with the plutonium.[5] But to keep the plutonium isolated for many millennia, the deployment hole must also avoid faults in the rock mass. The influence of horizontal, angled, and vertical faulting has been modeled, and it is clear that holes must not be located near vertical faults that might allow radionuclides to migrate toward the surface. If the borehole were connected at depth to a large, near-vertical fault and a similar connection were available near the top, density

[5] Data are provided in Svensk Karnbranslehantering AB, op. cit.

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differences between the fluid in the borehole and that in the fault (for instance, due to fission product decay heat in HLW or spent fuel—but not in weapons plutonium) would drive fluid circulation, leading to far more flow than would be available from circulation confined to the pore fluid of the borehole itself.

Thus, it will be necessary to characterize candidate regions for deep boreholes (using normal seismic techniques), and to make measurements from one or more pilot boreholes, in order to avoid emplacing containers in regions of major faulting. The possibility of major faulting over many millennia is one important area of uncertainty that requires further study. For similar reasons, it is important to choose drilling methods that will minimize cracking of the surrounding rock.

Another important issue is avoiding transport up through the hole itself. This is the purpose of the 2,000 meters of clay, asphalt, and concrete envisioned to seal the hole. Assuming that parts of the hole are likely to be saturated with groundwater, it is important to ensure that there are no ready means for convection in this water to transport radionuclides upward. For example, dissolved gas, heat, or differences in salinity could in principle reduce the density of the water in the part of the hole where the waste was emplaced (compared to the water above it), causing the lower water to rise slowly through the hole plug. Hence, it is important to choose materials for the waste package that do not generate more gas in the borehole (due to corrosion) than can be dissolved in the water (determined by the solubility limit at depth).[6]

The increased salinity of water at great depth may essentially eliminate upward convection—quite beyond the limits on convection posed by engineering means such as bentonite seals, avoidance of major faults, and the like. In general, when drilling deep holes, water is encountered whose salinity, in the words of the Swedish report, "increases dramatically with depth in most areas and in some cases approaches saturation." Because saline water is denser than fresh water, it could not rise convectively into an overlying region of fresh water, even if the saline water were heated (as it would be in the case of disposal of HLW). As the Swedish report concludes: "Clearly, a repository in a saline environment with fresh water above is highly desirable. If the water is highly saline, it appears that no radionuclides at all will be transported to the surface by convection."

Highly saline water may be found in drilling from islands or the seabed, or near the margins of the sea. For example, the Swedish study reports that "boreholes on the island of Gotland show a salinity content between four to eight percent, which is much higher than … the seawater today." In cases in

[6] For the disposal of spent fuel, the Swedish concept (ibid.) would probably involve casting the fuel rods themselves in copper. This would reduce the otherwise large void volume within canisters containing spent fuel assemblies, which (if undisplaced) would reduce the effectiveness of the clay seal after the canister corroded. Copper is suitable for the chemical environment common in granite in Sweden (a reducing, rather than an oxidizing, environment), though it would not be suitable, for example, for waste packages for the U.S. Yucca Mountain geologic repository.

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which the depth to saline water is greater than the depth of the nearby sea, there would generally be no convection upward of the dense saline water toward the sea—although upward transport could still occur (in principle) in the case of a pressurized aquifer, as in a large-scale Artesian well.

If the material to be disposed of generated substantial quantities of heat (as is the case with HLW and spent fuel), the decrease in density resulting from the warming of the surrounding water could lead to upward convection in the absence of such saline water, though it would still not rise through a major salinity gradient. This, however, is not relevant for the disposal of plutonium.

It is important to note that sorption of plutonium to the small particles in the clay or bentonite used to seal the borehole would provide another major barrier to its emergence. The effect is dramatic: the rate of diffusion through a material that is sorbing the plutonium is reduced by a factor known as the "distribution coefficient," Kd, which for bentonite might be factor of roughly 100,000.[7] In reality, however, the rate at which plutonium reaches the surface will be affected by the less effective and less readily analyzed sorption of plutonium on the particles in the small faults in the granite. But some preliminary estimates of the flow of water and plutonium through a partially sealed well can be made.

Assume, for example, an upflow in the hole of 1 cubic meter of water per year. Solubility of plutonium in analyses of repositories is often given as 10^{-3} grams per cubic meter; so if the water were fully saturated with plutonium, 10^{-3} grams would come to the surface each year. As described in the discussion of ocean dilution below, new U.S. regulations will enter into effect on January 1, 1994, limiting the allowable plutonium concentration in water to which members of the public might be exposed to 2×10^{-8} curies per cubic meter. To meet that standard, each gram of plutonium would have to be diluted in 4×10^{6} cubic meters of water. This standard would be satisfied by diluting the plutonium-saturated effluent assumed above with about 4,000 cubic meters of rainwater per year, which falls, on average, over an area of about 0.008 square kilometers (about 2 acres).

In reality, two factors would reduce the amount of plutonium transported to the surface still further: first, it will take water itself some 1,000 years or more to move to the surface in the well at the assumed flow rate. Second, and more important, most of the plutonium would be sorbed to the bentonite and other materials in the hole; the ultimate plutonium transport rate of 10^{-3} grams per year would be achieved only after the 2,000-cubic-meter bentonite column was loaded with plutonium. If plutonium is sorbed to them material used to plug the well with a distribution coefficient of 10^{5} (the ratio between mass sorbed per cubic meter and plutonium concentration in the pore water), then even at the

[7] For more on sorption and the distribution coefficient, see the discussion of sub-seabed disposal, below.

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assumed solubility of 10^{-3} grams per cubic meter, the bentonite column would be fully loaded with plutonium at $10^5 \times 10^{-3} = 100$ grams per cubic meter. Since there are 2,000 meters of bentonite and the plutonium is assumed to be flowing upward at only a thousandth of a gram per year (the solubility limit in the assumed water flow), it would take some two hundred million years for the bentonite to be loaded—10,000 half-lives of plutonium-239 (Pu-239).

More complex calculations are required to assess the degree to which plutonium might emerge through small faults in the rock, which would not have nearly the absorptive capacity of the bentonite-filled borehole. Recall, however, that the above calculations do *not* include the effects of salinity: if high salinity at depth can be guaranteed, even extensive faulting would not bring plutonium to the surface.

In short, it appears that if the borehole site is chosen appropriately, and the material emplaced correctly, only vulcanism or meteor impact would bring the material to the surface in significant quantities. The risks from either of these types of events are lower for boreholes than they would be for mined repositories, the closest comparison, because of the much greater depth of the boreholes.

The borehole option, however, would have to be analyzed for various accident possibilities during emplacement, in order to define facilities and procedures to reduce their likelihood and to provide means to proceed in case of accident. Borehole collapse during drilling would require redrilling, but collapse after emplacement of canisters begins is a more complicated problem that would need to be addressed during a development program for this option.

A set of open questions concerning the borehole option is described in Chapter 6.

Cost

Swedish estimates place the cost of deep-hole disposal of spent fuel in the range of $100 million per hole, although a Russian group advertises that it will drill a set of holes for much less.

There is clearly less processing necessary to transform weapons plutonium to a suitable waste form and to handle the resulting canisters than is the case for HLW or spent fuel, because of the intense gamma radioactivity of these latter products.

In any case, it appears certain that in the United States, the costs of development of the borehole option, and particularly of gaining the needed licensing and approvals (if they were eventually obtained), would substantially exceed the costs of the actual emplacement.

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Retrievability

The ability to monitor and retrieve the canisters, once emplaced, would be desirable from the point of view of ensuring that the system was working as expected. But retrievability is not a virtue if the goal of the disposal method is to create major barriers to reuse of the plutonium in weapons. At various times, deep-borehole disposal of canisters of high-level waste has been described as irretrievable, when that was considered desirable, or retrievable, when that was regarded as a virtue. As the Swedish report on this concept put it:

> It was initially thought that the VDH [very deep hole] concept would not allow the canisters to be retrieved once they had been deployed. Further consideration of this aspect of the concept indicates this not to be the case. There is no reason why the plugged section [of the original hole] cannot be drilled or washed out with high pressure fluids. Once the canisters have been reached they could be fished out using overshot tools, a standard oilfield practice. This procedure assumes that the canisters are still intact.[8]

As this quotation suggests, the simplest retrieval approach would involve redrilling the hole, which would be conventional, even easy, for the section filled with bentonite clay. In this way, one could reach the string of canisters and fish them out one by one, assuming they remained intact. The only major differences from conventional drilling would be the requirement to follow the pilot hole and the details of access to the canister. If the operation were to be conducted at a time when the canisters had ruptured or dissolved, a more complex approach requiring greater environment, safety, and health precautions would be needed, but the material would remain retrievable, at somewhat greater cost.

Clearly, however, it would not be possible for anyone to retrieve the plutonium without the permission of the host country, as long as political control in the host country remained intact. Moreover, because such drilling activities would be highly visible, the host country could not retrieve the plutonium without detection. Of course, what powers—if any—will control a particular borehole site after centuries or millennia have passed cannot be known.

To make retrieval more difficult, one might make the hole harder to redrill by embedding extremely hard material in the mud and concrete with which the hole is filled. One might make it more difficult to find the precise location of the hole by choosing a site in which the hard rock began at a depth of hundreds of meters or more from the surface, and by filling the zone above the sealed hole in the rock, and the region between there and the surface, with rubble. Still, if the location of the hole were known, it could eventually be found.

If the goal of retrieval were only to acquire a few tons of plutonium, and reactors and reprocessing facilities were available, it might turn out to be easier to make new plutonium or to separate reactor-grade plutonium from spent fuel;

[8] Svensk Karnbranslehantering AB, op. cit.

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but since the hole would only have to be redrilled once, retrieval from the deep borehole would probably be a cheaper route by which to acquire a large quantity of plutonium.

Policy Issues

While disposal in very deep holes appears technically feasible, and appears to offer the potential for superior isolation of plutonium from the biosphere, it has received far less critical study than has disposal of spent fuel and HLW in mined repositories. Thus, a substantial additional research and development effort would have to be focused on the deep-hole approach if this were to be a leading contender for plutonium disposal. The Swedish study suggests a future work plan that includes:

- continued review of data from past deep boreholes in crystalline rock;
- drilling-related research;
- research on plugging and sealing;
- modeling of water convection in and around the hole;
- pilot studies to determine the depth to saline water, using electromagnetic methods; and
- drilling of a 3-kilometer borehole, to test the geological assumptions.

The deep-borehole option is not yet ready for "development." In the absence of a crash program, it would take more than a decade to formulate a plan, carry out research on drilling and emplacement, and use existing holes to evaluate the effectiveness of sealing techniques.

A critical issue, at least in the United States, would be the likely difficulty of gaining the needed licenses and approvals for a deep-borehole disposal approach. As noted in Chapter 1, decades of effort and billions of dollars of expenditure have been devoted to developing the mined repository approach in the United States, and it is not expected that such a repository will be approved and opened for at least another two decades. In the case of the borehole approach, the relevant data would in some respects be more difficult to acquire. In the course of drilling the hole itself (and the smaller-diameter pilot hole), a great deal of data on the properties of the rock being drilled through and the geology of the site could be acquired. But to assess the homogeneity of the site would probably require drilling a number of additional holes to comparable depths nearby. (Means would have to be provided to ensure that these additional holes themselves did not provide a potential means of transport of radionuclides to the surface.) Even so, the degree of detail available on the geology of the area at 4,000-meter depth is unlikely to match that attainable for a mined repository at 500 meters. Finally, developing a technical licensing approach that did not rely on the monitoring and retrievability possible with a mined repository concept would be difficult and time-consuming.

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Management and Disposition of Excess Weapons Plutonium

These difficulties might be somewhat less in the different regulatory environment in Russia, but that cannot be predicted. Deep-borehole disposal might appeal to some Russian officials because it would permit eventual retrieval of the plutonium when its use as reactor fuel became cost-effective, while barring theft in the interim.

SUB-SEABED DISPOSAL

Description

As described in Chapter 6, disposal in the sub-seabed has long been the leading alternative to mined geologic repositories for disposal of spent fuel and high-level wastes. A detailed 1988 study by the Nuclear Energy Agency (NEA) of the Organization for Economic Cooperation and Development (OECD) concluded that "sub-seabed burial appears to be a technically feasible method of disposal of high-level radioactive wastes or spent fuel."[9] The sub-seabed option faces major problems of public and international acceptability as well as major legal restrictions, however. Moreover, a substantial period of further development would be required before it could be implemented. The U.S. program was canceled in 1986, and there is now no country in the world actively pursuing research and development on sub-seabed disposal.

The idea of sub-seabed disposal is to put the material in metallic canisters that would be placed in the "abyssal clay formation" several kilometers beneath the ocean surface. The canisters would be placed perhaps 30 meters below the surface of this deep ocean mud, which core samples demonstrate has been undisturbed in some areas for millions of years. This could be done by the use of free-falling "penetrators" dropped from ships, which would fall through the ocean and embed themselves in the mud; by a long drill stem from a ship; or by lowering an emplacement package by cable from a ship (see Figure 6-4).

An alternate concept would be to drill through these sediments into the bedrock below and place the canisters in holes drilled there. This in essence combines the deep-borehole and sub-seabed concepts. This approach would be

[9] See Nuclear Energy Agency, Organization for Economic Cooperation and Development, *Feasibility of Disposal of High-Level RadioactiveWaste in the Seabed* (1988), 8 volumes. The previous NEA/OECD study, *Seabed Disposal of High-Level Radioactive Waste* (1984) is also helpful. See also C.D. Hollister et al., "Subseabed Disposal of Nuclear Wastes," *Science*, 213, September 1981, pp. 1321-1326; U.S. Congress, Office of Technology Assessment, *Subseabed Disposal of High-Level RadioactiveWaste* (Washington, D.C.: Government Printing Office, May 1986); and *The Subseabed Disposal Project: Briefing Book 1985*, JK Associates, 1985.

This sub-seabed option in mid-ocean areas should not be confused with the idea that wastes should be placed in the "subduction zone," where one tectonic plate is slipping beneath another and the wastes would therefore be carried deep beneath the earth's crust. The problem with this approach is that even "fast" seafloor motions proceed at a rate of the order of 1 centimeter per year, meaning that in all of historic time (some 5,000 years) the material would only have moved 50 meters. Furthermore, the subduction zones are geologically active and unpredictable—prone to volcanoes, among other phenomena. For these reasons this report does not consider the subduction-zone option any further.

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substantially more costly, but might make the plutonium nearly impossible to find and recover once emplaced, which would address the retrievability problem discussed below. Because of the higher cost, however, and because preventing retrieval is not as serious an issue in the case of HLW or spent fuel, this concept of drilling through the abyssal mud to the underlying bedrock has not previously been examined in detail. The remainder of this discussion focuses on the more conventional approach of emplacing the canisters in the mud.

If, for example, 10 kilograms of plutonium were placed in each canister, the nominal 100-ton excess weapons plutonium stockpile (counting both U.S. and Russian plutonium) would require 10,000 canisters. If each of these weighed one ton, this would involve extremely careful sea transport and emplacement of about 10,000 tons of materials. Strict safeguards would need to be enforced over the operation of the ship in view of the high price that might be paid to steal even a small fraction of the cargo.

Environmental Impact

As with deep boreholes, the first question to consider is reliable isolation of plutonium from the environment. The mud of the abyssal plains has several advantages. It is located at depths of more than 4 kilometers, far from the edges of tectonic plates or other regions of geologic activity, and far from shorelines or other areas of human activity; as mentioned, it has been stable in some areas for millions of years. In what follows, one should note that such abyssal plains exist within the 200-mile exclusive economic zone (EEZ) of U.S. shores, a region that has different legal status from the broad ocean areas.

The barrier to release of the plutonium provided by the canister itself would be short-lived compared to the plutonium.[10] Hence the long-term barrier to dispersal is the mud itself.

The first issue is whether the hole created by the emplacement of the canister would quickly reclose. If not, this hole would provide a potential route for radionuclides to reach the surface. Modeling suggests that reclosure would occur very rapidly (within a fraction of a second) as a result of the large negative dynamic pressure (suction) associated with the high impact speed of the penetrator, but field experiments would be required to assess this prediction. This is a "make or break" question, and thus should be tested before any significant expenditures on other aspects of the option.

If the canisters were emplaced appropriately with the mud reclosed above them, the issue becomes: How would the plutonium move through the mud? The extremely fine particles of this abyssal mud greatly retard motion of water through them. Convective transport of plutonium in these sediments can be

[10] The best cladding material for the canisters yet proposed, an alloy designated as Ticode 12, has a corrosion rate of 6 millimeters per 1,000 years, compared to plutonium's half-life of 24,000 years. See Hollister et al., op. cit.

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treated in a fashion similar to that sketched for the deep-borehole option, by considering first the various driving forces for convection (density differences arising, for example, from heating or gas evolution, but also the very slow flow of pore water through the material) and then the transport of dissolved ions, taking into account the sorption of plutonium on sediment particles. Although it appears that convective transport of weapons plutonium could be reduced to extremely low levels by correct emplacement, convection is still likely to dominate diffusive transport over very long times since transport distances increase linearly with time for convection, and only as the square root of time for diffusion.

As in the case of the granite and bentonite described above, plutonium would be expected to bind to the mud particles, further delaying any possible movement. First, consider the movement without such adsorption. The rate at which a material will move by diffusion if it is not bound to particles in the medium depends on the diffusion coefficient D of the material in the medium. The mean square displacement of the material, $\langle x^2 \rangle$, is proportional to D and the time elapsed: $\langle x^2 \rangle = Dt$. The diffusion coefficient of dissolved plutonium may be estimated as some 2×10^{-6} cm^2/sec—some ten times lower than that of water itself. This would correspond to a root mean square displacement of about 25 meters (almost enough to reach the surface) in 100,000 years, at which time (4 half-lives of radioactive decay) roughly one-sixteenth of the original plutonium would remain. This is the expected diffusion in still water—that is, water immobilized in fine sand that does not sorb the plutonium.

Although some radionuclides (such as technetium) do not sorb on the mud particles and therefore would move through the mud at the rate described above, plutonium tends to bind strongly to the mud particles and therefore its motion through the mud would be drastically slowed.[11] As noted in the discussion of deep boreholes, such sorption is often described by using a parameter known as the "distribution coefficient," K_d.[12] The rate of diffusion through

[11] Each mud particle, however, has a limited number of surface sites capable of sorbing a particular class of charged atom, or ion, such as plutonium. Thus, the volume of mud immediately around the canister may become saturated with plutonium, at which point the remaining plutonium not yet bound to the mud will diffuse through it at the rates described above, as though no sorption were taking place. The mud's capability to bind plutonium might be saturated at a concentration of something like 1 kilogram of plutonium per cubic meter of mud, even if the plutonium concentration in the pore water is well below the solubility limit. At that concentration, the 10 kilograms of plutonium that might be held in a single canister would be sorbed in 10 cubic meters of mud, so the saturation zone would extend less than 1.5 meters from the canister itself. Hence this discussion focuses only on the simpler unsaturated problem.

[12] The units of K_d are milliliters per gram of sorbant—each gram of sorbant adds as much "hidden volume" as would K_d milliliters of actual solvent. For y grams of sorbant per milliliter of gross volume, and for $y \times K_d >> 1$, the mass of plutonium per milliliter of gross volume would be larger than that in the solution without sorbant by a factor $y \times K_d$; this applies to the linear range, for which K_d is nearly constant. Regarding the K_d concept, the 1984 NEA/OECD report (op. cit.) cautions that the various nuclides will be changing chemical form, making colloids, etc., all of which may behave differently.

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issue is the possible effect of the high temperature from the decay heat of the waste. This would make the surrounding pore water less dense, and hence buoyant. Studies to date suggest that "the thermally-induced movement of the pore waters, the waste package, and the sediments is small,"[15] but a major field test to assess this conclusion, the In-Situ Heat Experiment, was canceled in the late 1980s. In the case of excess weapons plutonium, this is not an issue because the heat output from the weapons plutonium would be only about 30 watts per canister (assuming 10 kilograms of plutonium could be placed in each canister), compared to some 1.5 kilowatts considered for the HLW case. Hence the weapons plutonium would raise the temperature of the mud at 1 meter by only 2-3°C, and the induced pore water flow would be less by the ratio of the heat produced.[16]

One issue that had not been fully addressed when the seabed studies were terminated is the existence of faults in some of the sediments examined, above and below the planned emplacement depths, which could create avenues for more rapid transport to the surface. For plutonium disposal, where only a small area is needed, one could simply avoid the known areas of faulting.[17] While one could imagine that living organisms might burrow through the mud and bring plutonium to the surface, tests indicate that such organisms exist only in approximately the top meter of sediment—though small organisms such as bacteria might well be brought to lower depths by the act of emplacing the canisters itself.

Even if the plutonium did reach the surface of the mud before it had nearly all decayed, it would be released in very deep water that does not mix rapidly with water at higher levels, and where concentrations of marine organisms are lower than they are near the surface—though seabed photography of these regions does show numerous benthic animals such as sea cucumbers. Preliminary modeling suggests that any doses to humans would be delayed many thousands of years and would be small compared to normal background radiation. (The dose to the most exposed population if much of the plutonium escaped into the sea is estimated below, in discussing the ocean dilution option.)

Another issue is possible criticality of the plutonium. A sustained chain reaction would greatly increase the heat in the emplacement, potentially creating a "bubble" of plutonium and fission products that would rise through the mud more rapidly than described above. To limit this risk, some processing of the plutonium would probably be necessary before emplacement. The canister could be filled with solid material, such as a plutonium alloy, or a cast matrix containing 3 atoms of normal boron per atom of Pu-239 (which is enough to keep

[15] NEA/OECD, 1988, op. cit., Vol. I, p. 42.

[16] If, however, the canisters were given the ability to pump a plutonium-bearing solution into the mud, as described below, this solution might be designed to have a different density than the surrounding water in the mud, causing it to either rise or sink very slowly.

[17] NEA/OECD, 1988, op. cit., Vol. 1, p. 20.

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the system subcritical). Boron, however, might leach away preferentially after the canister corroded, leaving the plutonium behind in a package moderated by seawater, which could lead to criticality; gadolinium, with its lower solubility, might prove to be a better choice. In addition to adding neutron-absorbing materials, the amount of plutonium placed in each canister might be limited so as to mitigate such criticality concerns. The design would have to prevent chain reactions not only for single canisters successfully emplaced, but in accident scenarios as well, in which multiple adjacent canisters might be immersed in water—as a result of accidental flooding of the ship's hold, for instance. That, however, would be an easier problem than handling the less well-specified configuration that might evolve after thousands of years under the seabed. For both the deep-borehole and sub-seabed options, the question of long-term criticality after differential leaching needs to be addressed because the issue is quite different from those addressed in the studies of these options for the disposition of HLW.

As noted above, because of the extremely slow predicted movement of radionuclides through the mud, some studies have concluded that plausible human doses of radioactivity from spent fuel or HLW correctly emplaced in the sub-seabed would be many thousands of times lower than doses from natural background radiation. Doses to maximally exposed individuals from a worst-case accident, however, such as a ship bearing spent fuel or HLW that sank near shore with none of the canisters recovered, could be several times normal background.[18] The overall risk of a transportation accident would generally be greater for options like sub-seabed disposal that add ocean transport to the land transport required for all the options. The potential impact of an accident during shipment or emplacement requires further study.

Not surprisingly, the environment, safety, and health (ES&H) aspects of sub-seabed disposal are dependent on the details of the process. If this approach were to be pursued, either for spent fuel and HLW or for weapons plutonium, a phased and interactive program of analysis and testing would be appropriate, focusing first on the potential "showstoppers," with the goal of eliminating the option as quickly and cheaply as possible, or of discovering approaches that survive analysis and field test.

[18] See NEA/OECD, op. cit., 1984, 1988; M.F. Kaplan and R.D. Klett, "Biological and Physical Oceanographic Sensitivity Analysis for Subseabed Disposal of High-Level Waste," SAND83-7107, Sandia National Laboratory, November 1984; and M.F. Kaplan, R.D. Klett, C.M. Koplik, and D.A. Ensminger, "Radiological Protection Options for Subseabed High-Level Waste Disposal," SAND84-0548, Sandia National Laboratory, March 1985, cited in U.S. Congress, Office of Technology Assessment, op. cit.

In this report's analysis of the ocean dilution option for disposal of weapons plutonium, the dose to the most highly exposed subpopulation identified in International Atomic Energy Agency (IAEA) studies is estimated in detail, for 100 metric tons of weapons plutonium injected into mid-ocean, without the barrier provided by the sub-seabed mud.

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Cost

The committee has not carried out an analysis of costs for disposal of plutonium in the sub-seabed. Past analyses for the case of spent fuel and HLW, although preliminary, suggested that the costs of sub-seabed disposal would be competitive with those of mined geologic disposal. But in the case discussed here, the cost of the repository must be considered "sunk," and only the net additional cost of adding this plutonium to it would have to be considered, whereas the entire cost of developing, demonstrating, gaining approval for, and implementing the sub-seabed option would have to be counted against the plutonium disposition mission. It appears likely that the cost of the actual emplacement would be in the range of a few hundred million dollars. The development and demonstration program necessary to meet licensing requirements might well cost billions of dollars (as in the case of land repositories).

Retrievability

As with deep boreholes, retrievability would be desirable from the point of view of ensuring that the disposal concept was working as expected, but undesirable if the goal was to create substantial barriers to recovery and use of this material in weapons.

The state emplacing the plutonium-bearing canisters could, and presumably would, maintain a detailed record of where the canisters were emplaced.[19] Given the distance from the ocean surface to the mud, retrieval could be handled by a major ocean-drilling ship; alternatively, it would be possible to develop a deep-water derrick that could be lowered from an ordinary ship, which could be positioned and repositioned on the seabed to retrieve one penetrator at a time. The deep-ocean drilling ships needed for the first approach have an operating cost of a few hundred thousand dollars a day, and less than a day would probably be required to retrieve each canister, corresponding to a recovery cost of perhaps $10,000 to $50,000 per kilogram of plutonium (not counting the cost of locating it in the first place). The seabed derrick option would probably be cheaper, after development costs were paid.

Similarly, other states with sophisticated deep-ocean technology that were aware of the approximate location of the disposal site would be able to find the canisters and recover them. The mud is homogeneous, with the consistency of "melted Godiva chocolate,"[20] and is quite transparent to sonar. Indeed, it is conventionally surveyed acoustically by sonar of various types, including very high resolution, towed near-bottom vehicles, and such sonar could locate the

[19] Indeed, in some concepts the penetrators would be equipped with transponders for this purpose, though the life of these transponders would be extremely short compared to that of the plutonium.

[20] C.D. Hollister, Woods Hole Oceanographic Institution, personal communication, November 3, 1992.

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canisters quite precisely years or centuries after emplacement. The canisters, if intact, could then be retrieved as just described. For less-developed countries and subnational groups, recovering plutonium by such means might be more costly and time-consuming than recovering plutonium from spent fuel, thus meeting the spent fuel standard. To limit such recovery possibilities, the area in which the plutonium-bearing canisters had been deposited could be monitored for an indefinite time, if that were agreed on. So long as the site was monitored, essentially nothing could move along the bottom without being detected. In that case, it is necessary to assess the cost of preventing retrieval, who will pay that cost, what kind of forces would have to be involved, and what country or group of countries would retain the responsibility. It is by no means assured that 1,000 years from now, for example, the United States will continue to exist or continue to maintain an interest in safeguarding plutonium disposed of in this way.

Alternatively, to avoid this requirement for surveillance and possible intervention, one might consider options to reduce the observability of the canisters (such as through "stealth" canisters designed to be difficult to detect by sonar) or to eliminate the canisters sooner rather than later. Such concepts have not been examined in the case of HLW disposal because preventing retrieval is not an issue for disposal of HLW, and because the canister provides one of the significant barriers to release of the radioactivity (since the lifetime of the canister is long compared to the period required for most of the radioactivity to decay). In the case of plutonium, preventing retrieval *is* an issue, and no material has been proposed that one can say with confidence will survive in ocean mud for the tens of thousands of years required for most of the plutonium to decay—which means that in limiting the total long-term hazard (as opposed to the early hazard), the canister is essentially irrelevant. A variety of mechanisms for eliminating the detectable canisters can be envisioned. These range from disintegrating the canister soon after emplacement by chemical dissolution or small explosive to doing without the canister in the first place, by injecting a plutonium-bearing solution into the mud with a small drill, to a depth comparable to that at which the canister would have been emplaced (with care taken to ensure that the hole created by drilling was appropriately reclosed).[21] A country with precise knowledge of the location of the disposal sites would still be able to "mine" the mud to recover the plutonium, but it seems unlikely that this would be competitive with recovering plutonium from spent fuel. None of these methods has been studied in any detail, but none seems to present fundamental technical obstacles. Close study of such methods and their ES&H implications would be essential to any further consideration of the sub-seabed option for plutonium disposition.

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[21] In concepts involving a plutonium solution injected into the mud, designers could in principle ensure that the plutonium-bearing "water" were somewhat denser than the water in the mud, meaning that it would gradually sink deeper into the mud with the passage of time, rather than rising toward the surface.

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Another solution to the retrievability problem, as noted above, would be to emplace the canisters in bedrock below the abyssal sediments, rather than in the sediments themselves. The canisters would then be in equally solid material, and would not be visible to sonar. Once a hundred meters or more of mud had reclosed over the hole in the rock, the hole would be extremely difficult if not impossible to find.

Policy Issues

As with the deep-borehole option, sub-seabed disposal would require significant additional development if it were to be a contender for plutonium disposal. At the time the U.S. program was canceled in the mid-1980s, it was estimated that another 25 years would be required before a sub-seabed disposal approach could be operational.[22] Development and emplacement costs are likely to be lower for the sub-seabed approach than for deep boreholes, but licensing and policy questions are much more problematic, whether a site in the broad ocean is contemplated or one in the 200-nautical-mile exclusive economic zone.

Sub-seabed disposal would face intense political opposition from many quarters, as well as a complex web of national and international legal hurdles and regulation. The U.S. Marine Protection, Research, and Sanctuaries Act, also known as the Ocean Dumping Act, forbids all dumping of high-level radioactive waste at sea and has been interpreted as including sub-seabed disposal.[23] Thus this legislation would have to be amended before the United States could implement the sub-seabed approach.

The London Dumping Convention of 1972[24] incorporates a similar prohibition on "ocean dumping" of high-level radioactive waste. The convention was negotiated before the sub-seabed disposal concept began to be widely discussed in the scientific community and thus does not mention the idea specifically.[25] The parties to the convention have never agreed on whether the agreement prohibits emplacement of wastes beneath the ocean floor, but a majority of the parties have expressed that view in the past. The parties have agreed that if the technical feasibility of the concept is demonstrated and one or more countries wished to pursue such a disposal approach, the convention would be the appropriate forum in which to consider the matter.

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22 JK Associates, op. cit.

23 ibid.

24 Formally known as the Convention on the Prevention of Ocean Pollution by Dumping of Wastes and Other Matter.

25 However, the IAEA, in a first draft of definitions for implementing the treaty prepared in 1973, mentioned the future possibility of burying wastes beneath the seafloor, and suggested that this should be considered as a variant of land burial, and therefore excluded from the convention. See NEA/OECD, 1984, op. cit.

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On November 12, 1993, the United States and 36 other nations voted to extend the convention to ban dumping of low-level radioactive waste as well, to impose a "permanent, legally binding ban on the dumping of all types of radioactive waste at sea." Belgium, Britain, and Russia abstained, and 29 of the 71 signatories to the 1972 London Dumping Convention were absent from the meeting. Proposals for an explicit prohibition on sub-seabed disposal are reportedly slated to be discussed in 1994 or 1995. At a minimum, it is clear that any proposal for sub-seabed disposal would require the acquiescence of a majority of the parties to the convention and that such approval might be very difficult to attain.

Further, the Law of the Sea Treaty, if it enters into force, would create an international authority that would regulate activities on the seabed, which would presumably assert authority over sub-seabed disposal. In addition to this legal framework, any proposal for disposal in or below the oceans is likely to provoke intense public and political opposition, both within the United States and internationally.

In short, gaining approval from a majority of the parties to the London Dumping Convention for sub-seabed disposal of plutonium, and overcoming the political, legal, and regulatory hurdles (including providing experimental data that do not yet exist) would be difficult, uncertain of success, time-consuming, and expensive. Furthermore, it appears that the sub-seabed option for disposal of weapons plutonium is different in fundamental ways from the sub-seabed option for disposal of high-level waste.

DILUTION OF PLUTONIUM IN THE OPEN OCEAN

Description

Another possibility is to dilute the plutonium in the open ocean, striving to achieve maximum mixing with ocean water so as to reduce the concentration of plutonium in any one location. By this method, one could relatively cheaply and quickly make the plutonium so dilute as to be completely irrecoverable.

If only the nominal 100 tons of excess weapons plutonium were disposed of in this way (rather than the much larger global stock of reactor plutonium, discussed below) and if it were possible to dilute it uniformly in the entire ocean —which has a volume of roughly 1.4×10^9 cubic kilometers—the resulting concentration would be 7×10^{-14} grams per liter. In an average liter of seawater, one atom of plutonium would decay to uranium every three hours (10^{-4} disintegrations per second). The natural concentration of uranium-238 (U-238) in seawater, 3×10^{-6} grams per liter, creates a background disintegration rate 300 times greater than 100 tons of plutonium would contribute.

This calculation is misleading, however, because it is not remotely possible to mix the plutonium evenly throughout the ocean, biological processes will reconcentrate the plutonium, and one cannot compare the toxicity of plutonium

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and uranium by looking only at the disintegration rate. The great difficulty of adequately ensuring that there would not be dangerous reconcentration of plutonium, the high probability of intense public and international opposition, and legal hurdles even higher than those facing the sub-seabed option probably make this option infeasible.

Environmental Impact

Existing regulations, national and international, provide a framework in which to consider the environmental impact of diluting 100 tons of excess weapons plutonium in the ocean.

In the United States, new regulations enter into force on January 1, 1994, limiting the allowable plutonium concentration in water to which members of the public might be exposed to 2×10^{-8} curies per cubic mater.[26] These limits were set with the goal of ensuring that a person drinking 2 liters a day of this water would receive a radiation dose of no more than 50 millirem per year. To remain below this new limit, each gram of weapons plutonium would have to be diluted in 4 million cubic meters of ocean water.

If one set a criterion that the concentration of plutonium even when first released from the dilution ships should not exceed this legal limit, then the ships would have to dilute the nominal 100 tons of plutonium into 400,000 cubic kilometers of water. To do this, one might use ships or submarines with long drag lines containing thousands of nozzles, dispersing plutonium solution at depths of several kilometers beneath the surface of the ocean. A single ship or submarine proceeding at a rate of 10 kilometers per hour would cover 240 kilometers per day. If it towed a drag line equipped with a tree-like array of perhaps 3,000 nozzles, spanning a depth range of 2 kilometers (at a mean depth of perhaps 4 kilometers), with the nozzles extending some 250 meters to each side of the line, the cross-sectional area into which the plutonium would be dispersed would be some 1,000,000 square meters, or 1 square kilometer.[27]

[26] These are new Nuclear Regulatory Commission limits (see *InsideNRC*, May 4, 1992, p. 3). For plutonium, these limits are 250 times more stringent than previous standards, which can be found in the *Code of Federal Regulations*, Vol. 10 (Energy), Part 20 (Standards for Protection Against Radiation), rev. 1 (Washington, D.C.: U. S. Government Printing Office, January 1992), pp. 321-457. The previous limits were based on an allowable dose 10 times higher, and a belief that plutonium ingestion was less effective in generating radioactive doses than new studies suggest.

[27] While the nozzles would be spaced a meter or two apart, the concentration in the column of water to which they were adding plutonium would quickly become uniform. If the eddy diffusion constant D_e in the deep ocean is roughly a typical 1 cm^2/s, then without any induced turbulence, even with nozzles spaced at intervals L of 18 meters, the affected column would be rendered uniform in plutonium concentration in about $(L/2\pi)^2/D_e = 1$ day. (See S.M. Flatte, ed., *Sound PropagationThrough a Fluctuating Ocean* (Cambridge, U.K.: Cambridge University Press, 1979), p. 7. Even in unusually still ocean depths, it would seem to be a simple matter to arrange the towline structure to provide enough small-scale turbulence to mix the injected fluid very quickly within the 1-square-kilometer trail. To leave random motions of 1 cm/s over this trial from a ship moving at 10 km/hr corresponds to an increased towline power of 200 kilowatts.

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Thus, such a ship could disperse plutonium into 240 cubic kilometers each day, and some 4.6 ship-years would be needed to reach the required 400,000 cubic kilometers into which to disperse 100 tons of plutonium.

International regulations would also apply to this case. As noted above, the London Dumping Convention forbids all disposal of high-level radioactive waste into the sea, and a majority of the parties to the convention have recently voted to bar low-level dumping as well. Any proposal to dispose of tens of tons of weapons plutonium in the ocean would surely be seen as directly contrary to the intent of the convention, even if the material could be diluted enough that it would meet current standards for disposal of low-level waste. Nevertheless, a discussion of what would be required to meet those standards is of interest.

Those standards, set by the IAEA, are slightly less stringent in their objectives (aiming to limit doses to the most exposed individuals to 100 rather than 50 millirem), but they include two factors not considered in the U.S. drinking water regulations. First, the IAEA limits are based on the assumption that the radiation releases in question should not be approved unless it would be acceptable for them to continue for 1,000 years. For the case of a one-time disposal of weapons plutonium, the assumption of continuing releases would not be correct (though it would be if the continuing global production of reactor plutonium were added, as discussed below); but this continuing release assumption nevertheless forms the basis for existing regulations. (The underlying principle of this approach is that our generation should not claim a greater right to or need for the capacity of the ocean to absorb radiation than later generations will have available to them.) Second, the IAEA regulations take into account the fact that some form of sea life concentrate plutonium in their edible tissues. Molluscs accumulate plutonium in their edible tissues at concentrations 3,000 times higher than those in the surrounding water; edible seaweed, 2,000 times; crustaceans, 300 times; and fish, 40 times.[28] The IAEA estimates that some coastal populations consume 600 grams of seafood per person per day, consisting of 300 grams of fish and 100 grams each of crustaceans, molluscs, and seaweed.

Applying the IAEA approach (continuing releases assumed, bioconcentration in species consumed by humans taken into account) to the U.S. regulatory standard would lead to much more stringent concentration limits. Consider first the bioconcentration issue. The U.S. drinking water standard is based on an exposed individual consuming 2,000 grams of water a day; if, instead, that individual consumes seafood at the rate and with the concentrations estimated by the IAEA, the concentration must be reduced by a factor of 270 to maintain the same radiation dose. Thus, to limit doses to exposed populations to 50 millirem per year (as the U.S. law requires), the volume of ocean into which 100 tons of weapons plutonium would have to be diluted would not be 400,000 cubic

[28] International Atomic Energy Agency, *Definition and Recommendationsfor the Convention on the Prevention of Marine Pollution by Dumpingof Wastes and Other Matter*, Safety Series No. 78, 1986 Edition (Vienna: IAEA, 1986).

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kilometers, as estimated above, but more than 100 million cublic kilometers. This is more than three times the volume of the mixed surface layer of the oceans, and nearly 8 percent of the volume of the entire ocean.

It is extremely unlikely that the plutonium could be successfully mixed into such a large volume, with no local "hot spots" where the concentration would be significantly higher, at any reasonable level of effort. For example, with ships such as those envisioned above, more than 1,000 ship-years would be required, assuming that one could somehow guarantee that one ship was not adding plutonium to the same volumes of water that other ships had. Moreover, this figure assumes that the weapons plutonium is allowed to consume the entire legal limits for radioactivity of this volume of water, with no other sources of radioactivity permitted for as long as that plutonium, with its half-life of 24,000 years, remains. If one adds to this the problem of limiting the equilibrium concentration, on the IAEA's assumption of releases that continue for 1,000 years, the problem would grow even more difficult.

All this assumes that the dilution would proceed without incident. If, for example, one of the ships collided with another ship and the plutonium was released, or one of the lines used collided with something else, resulting in greater plutonium releases, a local plutonium "hot spot" would be created.

All of the above calculations assume that the weapons plutonium alone would be allowed to pose the maximum allowable risk. Clearly this would make it impossible to dispose of other radioactive elements in the oceans without exceeding the regulations on maximum permissible doses. Moreover, in Chapter 6, the committee argues that if options for eliminating weapons plutonium nearly completely from international human access involve substantial additional risks, costs, or delays compared to options that make it as inaccessible as plutonium in spent fuel—as the ocean dilution option would—these additional problems should not be borne unless global stocks of civil plutonium are to be treated in a similar way. The excess global stock of civil plutonium is drastically larger than the excess weapons plutonium stock (some 800 tons compared to 100 tons), more toxic (roughly seven-fold, as a result of the presence of more of the more radioactive isotopes), and growing (by approximately 70 tons per year). To keep the dose to an exposed population consuming 600 grams a day of seafood below the legal limit would require diluting the reactor plutonium that already exists in a volume more than three times as large as the entire volume of the oceans.

Cost

The implementation cost of diluting 100 tons of weapons plutonium in the oceans in this way would be minimal, if the requirement is simply to meet the 1994 U.S. standards for fresh drinking water (without considering bioconcentration or continuing releases). The cost would amount to several tens of millions of dollars for ship modifications and for operations for only a few ship-years.

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But meeting the new standards while taking into account the bioconcentration that would increase doses by a further factor of 270 would require larger nozzle arrays and additional ship-years, thus raising costs. These implementation costs would in any case be greatly exceeded by the likely costs of the studies and licensing efforts that would ultimately be involved if this approach were to be seriously pursued.

Retrievability

In this case, the plutonium would be so dilute that there is no possibility of intentional retrieval. This is one of the few absolute statements possible in the complex subject of plutonium disposition.

Policy Issues

As noted above, public and international opposition to any such proposal—based on the environmental objections already outlined—would predictably be so overwhelming as to effectively rule out ocean dilution as a viable option.

Moreover, even more than the sub-seabed concept, ocean dilution would face a number of national and international legal hurdles. The U.S. ocean dumping law would presumably be interpreted as forbidding this option, as with the seabed option. As noted, the majority of the parties to the London Dumping Convention, including the United States, have voted to bar dumping of low-level radioactive waste as well as high-level waste. Such a ban would make all the preceding calculations concerning IAEA regulations on low-level waste disposal academic, unambiguously forbidding an ocean dilution approach.

SPACE DISPOSAL

Description

Disposal by launching into deep space has been studied extensively for disposal of high-level waste and could also be considered for plutonium.

In this option, a number of rockets would be used to launch the plutonium onto a path unlikely to encounter the earth. The plutonium would have to be placed in packages designed to limit any possible releases in the event of a major rocket failure (such as explosion on the pad or during ascent or reentry from a failed orbit). The safety risks, cost, delay, likely intense public and international opposition, and other aspects of this approach do not seem to put it high on the list of options. Even if space disposal were economically competitive, the design, demonstration, and operation of the systems required for high-reliability launch and high-confidence handling of inevitable accidents are daunting.

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Environmental Impact

The main risks in this case would result from potential launch accidents, reentry from failed orbits, and if launch had been successful, possible long-term risks of collision of the payload with meteors in space.

For example, a 1980 study examined the risk if a payload carrying HLW in a "cermet" (metallic ceramic) waste form were to reenter the atmosphere from a failed orbit.[29] The study predicted that with the package design envisioned, 11 percent of a 5-metric-ton waste package would burn up during reentry. The study estimated that the result, depending on circumstances, would range from "a few cancer deaths to as many as 100 or so" (for HLW rather than plutonium).

Space disposal of plutonium would require designs that would reliably prevent criticality accidents (which are not a problem in disposal of HLW). On the other hand, however, the minimal gamma radiation from plutonium makes the design and conduct of the missions easier than for HLW. There is little doubt that large (multiton) or small (10-kilogram) payloads of weapons plutonium can be designed that would reliably survive plausible accidents, including launch explosions or fires, reentry into the atmosphere, and high-speed impact on the ground—although demonstrating such safety to regulators and the public would be problematic. Yet, unlike HLW, the plutonium payload, if it returned to earth intact, would be a matter of great concern because it could be used to fabricate nuclear weapons. Thus, the inevitable risk of launch accidents is a fundamental problem for the space disposal approach.

Launching the plutonium into low-earth orbit (which requires a velocity of about 8 kilometers per second) would not be sufficient, because material in low-earth orbit falls back to earth on a time scale shorter than the decay time of plutonium. Therefore one would have to launch the material into an orbit around the sun unlikely to encounter the earth (which requires at least 11 kilometers per second (km/s)), to a path that will escape the solar system (16.8 km/s), or into the sun itself (more than 18 km/s).[30] Because the rocket launch mass required grows exponentially with the required velocity, options requiring high velocity would greatly increase the cost of the project.

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[29] For an exhaustive analysis of the issues involved, see *Analysisof Nuclear Disposal in Space*, Vol. I, Executive Summary, and Vol. II, Technical Report, Phase 3, Battelle Columbus Laboratories, March 31, 1980.

[30] The velocity requirement from the earth's surface for rocket propulsion into the sun is often quoted as 32 km/s—sufficient to overcome the earth's potential well (measured by the escape velocity of 11 km/s), while retaining a velocity of 30 km/s to cancel the earth's orbital speed. (The kinetic energy is proportional to the square of the velocities: 322 = 112 + 302.) However, it is clear that in principle, 16 km/s would suffice to reach the sun if the rocket almost escaped the solar system and then used a very small delta-V to cancel its tangential velocity so that it then falls into the sun. Specifically, a rocket burn giving 16 km/s near the earth's surface will carry the rocket around the sun to 18.25 astronomical units, at which time a retro-fire of 2.26 km/s will allow the payload to drop radially into the sun. The total delta-V in this example is thus 18.26 km/s, rather than the 32 normally considered—not much more than the 16.8 km/s required to escape the solar system.

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If the payloads were successfully launched, the main long-term hazard would be dispersal of the plutonium after collision with a meteor—a risk that applies only to the options involving continuing orbit around the sun, rather than escape from the solar system or disposal in the sun itself. The 1980 study estimated that the probability of a collision that would release even 0.2 percent of the payload in small particles would be about 4 parts per billion per year, while complete fragmentation (meaning collision with a larger meteor) would be 100 times less probable.[31] Thus, unless the payload were extremely unlucky, the plutonium would have completely decayed to uranium by the time a collision with a meteor might occur.

If the payload were in a circular orbit at 0.85 astronomical units (AU) (85 percent as far from the sun as the earth) the study estimated that 0.12 percent of the fine particles resulting from such a collision would fall to earth, taking an average of 100,000 years after the collision to do so. In contrast, if the payload were placed beyond earth's orbit, at 1.19 AU, 6.7 percent of the small particles produced in a collision will intercept the earth, taking an average of only 50,000 years to do so.[32]

The concept of launching the material directly into the sun would eliminate any risk that the plutonium would re-encounter the earth, but it would require a higher velocity (more than 18 kilometers per second) than any of the other options.

Cost

The cost of this approach would depend on the mass of the material that had to be launched, the velocity that the material had to reach, and what new systems had to be developed.

The mass that needs to be launched would be much more than the mass of the plutonium itself. First, one must consider that the plutonium should be in a form that will reliably be noncritical even if, for example, an accident results in it being immersed in ocean water. Thus, the plutonium must be combined with some neutron-absorbing material. Detailed calculations show that $PuO_2 \times 3B$ is subcritical in any quantity, density, or configuration (using boron of normal isotopic composition); it is 81 percent plutonium by weight.[33] The reentry vehicle (RV) needed to ensure integrity in the event of an accidental explosion or reentry from orbit would roughly double the mass of the composite. Thus, the overall RV mass would total 2.5 times the mass of the contained plutonium.

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[31] *Analysis of Nuclear Disposal in Space*, op. cit.

[32] This major difference arises from the Poynting-Robertson drag on the small fragments, which encounter more solar radiation on their leading face than on the trailing face, thereby experiencing a relativistic drag that forces them to spiral in toward the sun.

[33] J. L. Richter, Los Alamos National Laboratory, personal communication, April 1993.

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The concept usually discussed for space disposal is to begin by launching the material into a circular low-earth orbit (LEO) at roughly 300 kilometers altitude (which requires a rocket velocity gain of some 8 km/s), and then to use an additional burn to move the material onto the desired deep-space path, whether to another orbit around the sun, to escape from the solar system, or to go into the sun. Such staging from LEO is the least-energy and probably the least-cost approach. An appropriately timed additional burn of some 3.4 km/s in LEO would place the payload at a radius of 0.85 AU from the sun six months later, and a further burn of 1.16 km/s will place the payload into a circular orbit of radius 0.85 AU, inclined 1° to the plane of the ecliptic. If one assumes a solid propellant of equivalent specific impulse (I_{sp}) of 200 seconds (corresponding to an exhaust velocity of 2 km/s, instead of detailed computation using a real I_{sp} of 270 seconds, which would then be reduced by reasonable mass fractions for structure, tanks, and engines), the combined velocity gain of these two last burns (4.51 km/s) would require a mass ratio of 9.5:1 between the rocket mass in LEO and the final inert payload in circular solar orbit.

The initial velocity gain to LEO of 8 km/s at an I_{sp} of 200 seconds corresponds to a mass ratio of 55 from launch to LEO, which combined with the 9.5:1 means an overall mass ratio of 524:1. Thus, launching 10 kilograms of plutonium would mean an overall RV mass of 25 kilograms, a mass in LEO of 238 kilograms, and a launch mass of 13 metric tons.

Today, large payloads cost roughly $10,000/kg to launch to LEO. At this cost, launching the 238-kilogram payload to LEO would cost some $2.4 million, or about $240 per gram of plutonium. The launch costs for disposing of 100 tons of excess weapons plutonium in this way—not including any other costs, such as development and licensing—would come to $24 billion.

Thus, without any consideration of extra costs for development, licensing, rescue of the payload, or tracking and prompt retrieval of an aborted launch or reentry, one finds a cost that is truly out of sight in comparison even with building dedicated power reactors to consume the plutonium.

Can launch costs be reduced? Probably so. A variety of new launch concepts have been proposed in recent years; at one time the goal of development in the Strategic Defense Initiative (SDI) program was to reduce launch costs 100-fold compared to today's prices. For this mission, it may be that smaller rockets would turn out to be cheaper than large heavy-lift vehicles, because of the great miniaturization that is now possible, and the economies of scale in procuring many units of a single design, together with the much reduced cost of development of a small rocket compared with a large one of comparable technology. If 10 kilograms of plutonium were launched on each rocket, some 10,000 launches would be required to dispose of 100 metric tons of military plutonium.

How low would launch costs have to go to make space launch competitive with reactor or vitrification options that would cost $2.5 billion or less? If one imagines 10,000 launches, then $1 billion allocated for sensors and electronics

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would require that this element of each launch not exceed $100,000. The remaining $1.5 billion would be consumed at an average cost for engine, structure, and fuel of $10 per pound. With many thousands of ballistic missiles built over the years, however, no such modest costs have been achieved, and the extreme reliability required for launch of plutonium payloads is likely to increase the cost beyond that associated with a system based on consumer-standard components.

Moreover, developing and licensing the launcher and reentry vehicle, and developing, demonstrating, and building a highly reliable rescue system for payloads that might get stuck in LEO—the only way to prevent their eventual fiery return to earth—would be substantial additions to the total cost.

DESTRUCTION WITH UNDERGROUND NUCLEAR EXPLOSIONS

Description

Shortly after the dissolution of the former Soviet Union, the Russian firm CHETEK, associated with the Russian nuclear weapons laboratory Arzamas-16 and the Ministry of Atomic Energy, proposed that plutonium could be disposed of by using underground nuclear explosions.[34] A single 50-kiloton device could be surrounded by some 5,000 plutonium pits. The 50-kiloton blast would melt both the pits and 50,000 tons of the surrounding rock, into which the plutonium from the pits would be dissolved and distributed. Several such blasts would be required to dispose of the pits from the tens of thousands of nuclear weapons now slated to be dismantled.

More recent proposals are to destroy perhaps 100 pits at a time by using much smaller nuclear explosions. This would require the same excavation per pit as the more aggressive proposal, about the same total nuclear explosive yield, but more underground detonations.

Another possibility would be to use this approach to destroy intact nuclear weapons, saving the time and cost of disassembly. One-point safety calculations would be needed for this case because the weapons would be affected by a nuclear blast wave combined with substantial numbers of neutrons from the original explosion. This option would also throw away the substantial value of the highly enriched uranium in the weapons.

These concepts raise obvious environmental and policy issues; CHETEK no longer appears to be actively pursuing the idea.

[34] See, for example, proposal by Y.A. Trutnev and A.K. Chernyschev (Arzamas-16), presented at the *Fourth International Workshop on NuclearWarhead Elimination and Nonproliferation*, Washington, D.C., February 26-27, 1992.

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Environmental Impact

The safety of such an operation has not yet been sufficiently analyzed, but need not be, since the idea can be rejected on other grounds.

This concept would amount, in effect, to placing 100 tons of plutonium into an underground repository. In this case, however, the waste form would be created explosively, with no ability to ensure that it was a suitable form for disposal, and it would be located at a site never intended as a geologic repository. Either factor alone would essentially rule out this option from competition with approaches in which the waste form is carefully engineered and placed in an engineered repository. For example, concerns over potential long-term criticality of the underground plutonium, after possible differential leaching of different constituents in the rock, would be far more difficult to address than in the case of the vitrification or spent fuel options, since there would be no opportunity to engineer the resulting waste form with this problem in mind. Furthermore, a much larger surface area of plutonium-bearing material would ultimately be exposed to water than is the case in an engineered repository.

The explosion would be situated either above the water table (which is at a depth of some 550 meters at the Nevada Test Site) or below it. If above, then rainwater may penetrate the debris and transport the plutonium into an underlying aquifer. If below the water table, flowing water may transport the debris. Disposing of plutonium from tens of thousands of weapons in this way would mean a very large increase in the amount of plutonium already at the U.S. and Russian test sites, from hundreds of past tests.

Cost

The size and depth of the hole in which the explosion was carried out would significantly affect the cost of this option. CHETEK has referred to placing the pits in a mined cavern, but it would probably be cheaper to use a relatively normal drilled hole of some 8-foot (2.4-meter) diameter.[35] To avoid venting of the explosion, normal test practice calls for a depth of burial that increases with the one-third power of the explosive yield, according to the formula $B = 125Y^{1/3}$ (with B in meters and Y in kilotons). This gives a depth of 125 meters for a yield of 1 kiloton, and 270 meters for 10 kilotons.

For example, one might use a 1.3-kiloton explosive detonated at a conservative depth of 300 meters. Since such an explosive will create a cavity with a radius of about 15 meters, one could imagine placing racks of pits above and below the explosive, each holding ten bays, 5 feet apart, each loaded with five warheads or pits, for a total of 100 to be destroyed by this blast. Alternatively, one could pack the pits considerably tighter. Using the Russian-design pit storage containers—50 centimeters in both diameter and length—and stacking

[35] C.J. Anderson, W.G. Sutcliffe, et al., Livermore National Laboratory, personal communication, January 25, 1993.

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them with 50 percent volume efficiency (four containers per cubic meter), one could put as many as 1,200 pits into the cavity for a 1-kiloton explosive. Yet another approach would be to use a string of explosives, each with its 100-1,000 target pits, installed in the same hole and detonated simultaneously. Since a 2.5-meter hole 300 meters deep in Nevada costs about $1 million, the cost would be $10,000 per pit destroyed just for the hole (at 100 pits per hole); for 20,000 pits, the cost would be $200 million. There would be additional costs for the nuclear weapon used and in overhead for the various preparations required; the overall program cost for a single 100-pit destruction event might be $20-$30 million. Perhaps after the first several, the cost would drop to about $10 million per shot, for a per-pit cost of $100,000 and a total program cost for 20,000 pits of $2 billion. This does not include costs of development and licensing.

Retrievability

In addition to the environmental and other policy issues associated with this approach, the plutonium would remain readily retrievable for the host nation. If everything goes as claimed, in the aggressive approach involving 5,000 pits at a time being destroyed by 50-kiloton blasts, an average of one pit would be dissolved in 10 metric tons of melted and solidified rock. Similarly, for the concept involving 100 pits destroyed by a 1.3-kiloton explosive, there would be one pit in every 13 tons of rock. If 1,200 pits were packed around such a 1.3-kiloton explosive, there would be one pit in every ton of rock. The only fission products in this rock would come from the single nuclear explosion, and thus the rock would be much easier to handle than spent fuel, even if that fuel were many decades old.

Since gold can be mined profitably at a level of 1 ounce per ton (at a market price of some $10 per gram), it is clear that any of these options would create a very rich plutonium mine. On the other hand, casual access to the plutonium would be precluded, and that would be of some value.

Policy Issues

Clearly public opposition to this disposal method would be intense. Moreover, setting off nuclear explosions for this purpose would contravene the current moratorium on nuclear testing, and undermine the current U.S. and Russian policy of pursuing a comprehensive ban on nuclear explosions.

BRIEF SUMMARY OF CONCLUSIONS

Of these five options, all but deep boreholes and the sub-seabed approach may be rejected at this stage. Disposal of plutonium in containers in deep boreholes merits further analysis and evaluation. Sub-seabed disposal should be

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explored further, but only in a form in which the plutonium is injected into the surrounding mud, rather than remaining contained in a set of compact canisters that could be readily located. It should not be pursued over the objections of the international community.

Further exploration of these two options will evidently need to emphasize different aspects of the process. Deep-borehole disposal has many technical questions relating to the drilling of the hole, characterization of the environment, emplacement of the containers, and sealing of the borehole. The continued isolation of plutonium from the biosphere can be investigated rather independently, including the potentially important benefit of highly saline water at depth. Policy issues play a minor role in deep-borehole disposal.

The sub-seabed option, on the other hand, poses major policy questions. The technical aspects of injection of plutonium solution into the deep-ocean sediment are relatively simple technically, and a program for analysis and field test of the isolation provided by the sediments can be laid out that would have high confidence of resolving the necessary issues. The crucial aspects of sub-seabed disposal are the policy implications, and these questions can be explored on the assumption that the technical aspects can be resolved satisfactorily. The policy issues may differ somewhat depending on whether the plutonium would be emplaced within the exclusive economic zone with 200 nautical miles of the United States or Russia, or in international waters—though the two zones are strongly coupled by ocean circulation and both are covered by the London Dumping Convention.

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