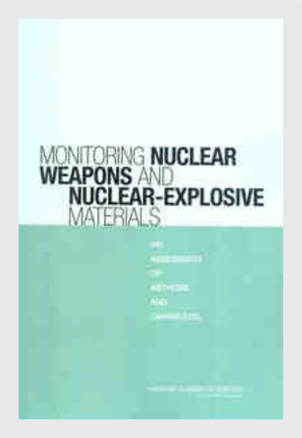

Monitoring Nuclear Weapons and Nuclear-Explosive Materials: An Assessment of Methods and Capabilities

DETAILS

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MONITORING **NUCLEAR WEAPONS** AND **NUCLEAR-EXPLOSIVE** MATERIALS

Committee on International Security and Arms Control

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Preface

This year marks the 60th anniversary of the first test of a nuclear weapon at Alamogordo, New Mexico on July 16, 1945. Within the next month, the United States dropped two nuclear weapons on Japan—on Hiroshima on August 6th and on Nagasaki on August 9th. We must all be profoundly thankful that no other nuclear weapons have been used in war since that time. The scientific and technical community, working with experts in many other fields, has played an essential role in the efforts that have prevented the further use of nuclear weapons thus far. But we are all too aware that one of the greatest challenges facing the world today is how to prevent their use in the future, either by nations or by terrorists.

The year 2005 also marks the 25th anniversary of the creation of the Committee on International Security and Arms (CISAC) by the National Academy of Sciences (NAS). CISAC was formed at a time when the risks to the world from nuclear weapons seemed to be increasing. During a time of extraordinary tensions in U.S.-Soviet relations, CISAC provided a nongovernmental channel of communication between Soviet and American scientists, as a vehicle for exploring ways to reduce nuclear dangers. For several years, the private, off-the-record dialogue between CISAC and its Soviet counterpart group was one of the few links through which well-informed, policy-connected individuals on the two sides could interact to pursue solutions to key technical problems related to nuclear arms control. Even after formal U.S.-Soviet arms control negotiations resumed, the CISAC-initiated dialogues continued to be invaluable, offering a vehicle for "back channel" discussions that were both less constrained and more analytical than those being pursued officially.

In the 25 years since it was founded, CISAC has broadened its efforts to include: bilateral dialogues and related workshops with similarly constituted groups in China and India; bilateral and multilateral meetings with European academies; the conduct of major studies of security and arms control problems and policies; the instigation of additional studies by specially constituted panels within the National Academies; and the organization of symposia and workshops to inform Academy members, the wider technical community, and the public at large about key issues at the intersection of science and technology with international security. These CISAC efforts have addressed not only nuclear issues, but also those connected with chemical and biological weapons, space weaponry and national missile defense, and conventional forces and the arms trade.

Two thousand and four brought a number of major changes to CISAC, including John Holdren's decision to retire as chair at the end of the calendar year, after over 10 years in that role. Under John's outstanding leadership, a number of CISAC studies have been carried out that have helped to shape the debate in the United States and overseas about critical technical issues, as well as about larger questions concerning the directions of nuclear weapons policy. And CISAC's dialogues have remained a source of ideas and continuing contact with influential counterparts in countries vital to U.S. security interests. CISAC's long record of success has made the committee a positive force in policy formation—both by the U.S. government and overseas.

In this study, CISAC tackles the technical dimensions of a longstanding controversy: To what extent could existing and plausibly attainable measures for transparency and monitoring make possible the verification of all nuclear weapons—strategic and nonstrategic, deployed and nondeployed—plus the nuclear-explosive components and materials that are their essential ingredients? The committee's assessment of the technical and organizational possibilities suggests a more optimistic conclusion than most of those concerned with these issues might have expected.

The study began with a request from the Department of Energy in 2000 to examine the potential for a more comprehensive approach to nuclear arms reduction. U.S. policy changed over the ensuing years in ways that reduced the immediate interest in more comprehensive formal agreements. But it became clear to the committee that the study's original technical focus on transparency and monitoring measures and methods would remain germane under a wide range of possible policy priorities, including the growing emphasis on nonproliferation and prevention of access to nuclear weapons and materials by terrorists. In fact, this report will be highly relevant to policy-makers and analysts of a variety of political persuasions and policy preferences.

Many committee members and staff have contributed to the final product presented here. The study chairs were Steve Fetter of the University of Maryland and Major General William F. Burns (USA, Ret.), reflecting CISAC's belief in the benefits that come from combining technical and policy expertise to address critical security problems. Their continuing dedication and patience through a long study process, as well as their central intellectual contributions to the effort, were indispensable. Spurgeon Keeny, CISAC member and Visiting Senior Fellow of the National Academies, served as Editor in Chief for the project starting in 2002, guiding the writing effort through multiple drafts to its successful completion. Substantial portions of the report were also drafted by then CISAC chair John P. Holdren of Harvard University and by CISAC chair emeritus, Pief Panofsky of Stanford University. Over the course of the study, all members of CISAC contributed key ideas and critical commentary leading to the final product.

A number of staff also contributed greatly to the study. David Hafemeister served as the initial study director and established the project's technical foundation. Christopher Eldridge and Ben Rusek provided essential research support at important stages of the project, and key portions of the study reflect their contributions. Matthew Bunn of Harvard University also served as an unpaid consultant and provided invaluable assistance, particularly on issues related to nuclear-explosive materials. La'Faye Lewis-Oliver ensured that the entire administrative process functioned smoothly, and Amy Giamis provided additional administrative support. Finally, CISAC staff director Jo Husbands undertook the challenge of ensuring that all of the contributions came to fruition, and she participated in the study as an intellectual partner.

The current report continues CISAC's tradition of providing quality technical analysis of relevance to key policy problems. The basic architecture for verification assessed in this study is built upon transparency and monitoring. It applies whether the focus is a few containers of nuclear-explosive material or an extensive nuclear stockpile containing thousands of intact weapons, weapons components, and many tons of nuclear-explosive material. The committee argues that these methods and capabilities are highly relevant to U.S. and international efforts to "address the urgent and interrelated goals of reducing the dangers from existing nuclear arsenals, minimizing the spread of nuclear weaponry to additional states, and preventing the acquisition of nuclear weapons by terrorists." I agree.

In closing, I want to take this opportunity to express my deep appreciation to John Holdren, Pief Panofsky, Spurgeon Keeny, and the other CISAC veterans who have now transitioned to become Senior Advisors to this committee. Their many years of dedicated service have made a tremendous contribution to both the nation and the world.

Bruce Alberts
President
National Academy of Sciences

Acknowledgments

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

We wish to thank the following individuals for their review of this report: Victor Alessi, United States Industry Coalition, Inc.; Paul Bracken, Yale University; Sidney Drell (retired), Stanford Linear Accelerator Center; Thomas Graham, Jr., Morgan Lewis and Bockius LLP; Roger Hagengruber, University of New Mexico; Robert Monroe, Bechtel Corporation; Leonard Spector, Monterey Institute Center for Nonproliferation Studies; and Frank von Hippel, Princeton University.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Harold Forsen (retired), Bechtel Corporation and Gerald Dinneen (retired), Honeywell, Inc. Appointed by the National Research Council, they were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

The Committee on International Security and Arms Control (CISAC) is a standing committee of the National Academy of Sciences. For purposes of administration, CISAC is part of the Policy and Global Affairs Division of the National Research Council.

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Executive Summary

THE SCOPE OF THE STUDY

This study has explored the extent to which current and foreseeable approaches to transparency and monitoring can support verification for all categories of nuclear weapons—strategic and nonstrategic, deployed and nondeployed—as well as for the nuclear-explosive components and materials that are their essential ingredients. We believe that increasing the categories of items subject to transparency and monitoring would be valuable—and may ultimately be essential—as the United States and the world attempt to address the urgent and interrelated goals of reducing the dangers from existing nuclear arsenals, minimizing the spread of nuclear weaponry to additional states, and preventing the acquisition of nuclear weapons by terrorists.

In the specific case of reductions in existing nuclear arsenals, we believe that more comprehensive verification would almost certainly be deemed essential if the United States and Russia decided to pursue substantially deeper cuts in nuclear weaponry than those agreed in the Moscow Treaty of 2002. Extending agreed limits to nuclear weapon states with smaller arsenals (for example, China, France, and the United Kingdom among the *de jure* weapon states and India, Pakistan, and Israel among the *de facto* ones) would likewise increase the desirability if not the necessity of more comprehensive verification.

The motivation and scope for this study were not confined to understanding the transparency and monitoring possibilities and requirements germane to more ambitious arms control regimes. The study has also focused on potential applications to the continuing challenges of keeping nuclear weapons out of the hands of proliferant states and terrorists; for example, the United States has emphasized the need for verification in the complete elimination of North Korea's nuclear weapons program. Likewise, as the United States continues to work with Russia to ensure that nuclear materials are adequately protected and accounted for, the partners will continue to require transparency measures to facilitate the process, as has been the case in the implementation of the 1993 Highly Enriched Uranium Purchase Agreement.

This study has addressed the technical and institutional approaches and capabilities in transparency and monitoring that could be applied to any or all of these purposes. It has not tried to analyze or make recommendations about the choices in U.S. nuclear weapon and nonproliferation policies and priorities that will continue to shape the context within which such approaches and capabilities might be applied.

THE CURRENT CONTEXT

The risks associated with the world's stockpiles of nuclear weapons, nuclear-explosive components of weapons, and nuclear-explosive materials (NEM)[1] include:

- the dangers in the potential for use of existing arsenals, including the possibilities of deliberate use of nuclear weapons by their authorized possessors and also the possibilities of accidental, inadvertent, or unauthorized use;
- the risks that the existing arsenals and perceptions about their characteristics and intended uses will provoke further, potentially destabilizing nuclear weapon developments and deployments either by the countries already possessing such weapons or by additional countries; and
- the danger that the existing stockpiles of weapons, components, and NEM will be the enablers rather than merely one of the motivators of proliferation, through illicit transfer to or theft by (or on behalf of) proliferant states or terrorist groups.

The risks posed by nuclear weapons are exacerbated in many respects by the size of the current arsenals and by the magnitude of the worldwide stockpiles of NEM. The United States and Russia possess about 95 percent of the approximately 30,000 existing nuclear weapons, with the remainder held by the United Kingdom, France, China, Israel, India, Pakistan, and possibly North Korea. Enough additional NEM exists in military and civil nuclear facilities worldwide to make something like 100,000 additional nuclear weapons. These stockpiles of NEM, in addition to presenting a

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[1] A "nuclear-explosive material" is a mixture of fissionable nuclides in which the proportions of these are such as to support an explosively growing fission chain reaction when the material is present in suitable quantity, density, configuration, and chemical form and purity. Uranium containing more than 20 percent U-235 or more than 12 percent U-233 (or an equivalent combination of proportions of these two nuclides) is considered NEM, as are all mixtures of plutonium isotopes containing less than 80 percent Pu-238. See Chapter 3 and Appendix A for more detail.

ready resource for further production of weapons by the states holding them, also constitute a potential source of materials that could be used for the fabrication of nuclear weapons by non-nuclear weapon states and even terrorist groups. Any assessment of the potential future availability of NEM, moreover, must include not only military stocks of these materials but also the NEM in research reactors and the growing quantities of it in civilian nuclear power programs.

The degree of transparency that countries have permitted concerning their nuclear weapons inventories and NEM has tended to increase over time, albeit with some reversals and persistent regional exceptions, because the countries agreeing to the increased transparency have regarded these changes as bringing bigger benefits than liabilities for their security. The benefits include improved opportunities for monitoring that can increase confidence in the verification of agreements and reduce the uncertainties in assessing potential threats that can feed worst-case scenarios. The liabilities against which such benefits must be balanced include the danger of revealing sensitive information that could aid proliferators or increase a nation's vulnerability to attack. Both the United States and Russia have moved slowly and cautiously to share information regarding even well-known aspects of their nuclear arsenals and remain reluctant to provide each other with information they regard as closely related to the details of weapon design. Countries with small nuclear arsenals have particularly acute concerns about sharing information regarding the locations of their nuclear weapons.

Most of the measures and technologies for transparency and monitoring assessed in this study were developed in the course of continuing efforts to find ways to limit the risks from existing nuclear arsenals and their proliferation to additional countries and groups. Attempts to limit numbers and characteristics of nuclear weapons and their delivery systems have often been controversial; belief in the value and practicality of nonproliferation efforts has also varied over time and across groups. Verification issues frequently have been at the heart of these controversies, with debates focusing on the likelihood of cheating and the capability to assess compliance in fundamentally adversarial circumstances. On a number of occasions, however, the bilateral or multilateral political will needed to increase transparency and the availability of suitable monitoring technologies for these purposes allowed the completion of measures and agreements—including some previously thought unattainable—in both the arms control and nonproliferation domains. Controversies about what is desirable and feasible in these domains will continue, as will caution about revealing too much. But opportunities will also continue to emerge to exploit capabilities related to transparency and monitoring.

Nuclear Weapons and Nuclear Weapon Components

Traditionally, the nuclear weapon life cycle was closed to outside scrutiny. Nuclear weapons in themselves, once produced, were not considered suitable candidates for direct, verified control because they are small, easily concealed, and cloaked in secrecy. The introduction in the early 1960s of reconnaissance satellites carrying high-resolution cameras and other sensors, as well as other "National Technical Means" (NTM), made it possible to monitor with confidence the numbers and types of strategic delivery systems, however. Counting strategic delivery vehicles (that is, missiles, missile launchers, and aircraft) became available as a surrogate for verifying the nuclear weapons themselves in determining and limiting the size of strategic nuclear forces. The maximum number of weapons that each type of land- or sea-launched ballistic missile was designed to carry could be determined by NTM, including the collection of telemetry from flight tests (which in an early and crucial manifestation of transparency the principal parties agreed not to encrypt).

Although nuclear weapons themselves have never been the subject of agreed direct verification, past and current arms control agreements have provided significant practical experience in the design and implementation of monitoring options for nuclear weapon delivery systems, including their production and storage. In addition, since the end of the Cold War, U.S. and Russian nuclear weapon laboratories have carried out substantial cooperative work on extending these arrangements directly to nuclear weapons and their components (as part of broader lab-to-lab programs of joint threat reduction activities).

Our assessments in this study support the conclusion that the necessary technical tools are either available today, or could be in hand with some additional development, to support significantly enhanced transparency and monitoring for declared stocks at declared sites throughout the nuclear weapon life cycle;

- Developments in cryptography now widely used in banking and other commercial transactions offer a way to exchange, in a limited and controlled but still very useful way, sensitive information about nuclear weapons that countries would not be willing to share more openly and comprehensively because of security concerns.

- Methods are available to examine from a short distance the radiation from a nuclear weapon or to interrogate a declared weapon container with an external radiation source. The radiation signature can be matched against templates of actual nuclear weapon signatures, or some portion of the radiation signatures can be singled out to identify attributes that confirm that the object is indeed a weapon. These techniques permit identification without revealing sensitive weapon design information.
- A wide array of tags and seals, ranging from bar codes and tamper-indicating tape to electronic chips, can be applied to containers and storage rooms for weapons and be interrogated to check their status.
- Monitored perimeter-portal systems, which exploit radiation and other distinctive signatures, can be installed and operated to confirm that what enters and leaves any given facility is what it is supposed to be.
- Facilities and areas within facilities can be equipped with appropriate sensors and accountability systems to monitor declared activity and detect undeclared activity, the recordings from which can either be examined during periodic inspections or uploaded via the Internet or satellites for transmission to a monitoring center.

This array of tools makes it possible to contemplate a set of transparency and monitoring measures that would cover declared stocks at declared sites during all stages of the nuclear weapon life cycle, which might include:

- Declarations of nuclear weapon stocks at progressively increased levels of detail, ranging from total numbers of weapons; to specification of numbers of different types, including their operational status and associated delivery vehicle; to declarations for each weapon by serial number, weapon type, status, and current location.
- Declarations of the name and location of all facilities at which nuclear weapons are currently deployed, stored, assembled, maintained, remanufactured, dismantled, or otherwise handled, along with detailed information about each site and its operating history.
- Continuous monitoring of weapon stocks at facilities at all stages throughout the nuclear weapon life cycle, either with personnel on-site or remotely.

- Confirmation of weapon remanufacture and assembly as well as weapon elimination.
- Provisions for routine on-site inspections at declared facilities to confirm declarations and any updates, as well as for inspections of both declared and suspect sites in the event of detection of suspicious activity or unexplained discrepancies.

Similar measures could be applied to nuclear weapon components. Depending on the design of the system, cooperative application of such measures would make it possible to confirm the accuracy of declarations of weapon stocks and to monitor weapon storage, assembly, and disassembly at declared facilities while protecting sensitive weapon design information.

Some of the less intrusive measures, such as declarations of current weapon stocks or of plans for future changes to those stockpiles, can have value in their own right as confidence-building measures. These measures could be undertaken unilaterally or through formal agreements. In general, however, tools and measures that provide a higher degree of confidence come at the cost of greater intrusiveness and potential impact on normal operations. They also require more effort to protect sensitive weapon design information. They are therefore more suited to formal agreements, where the rules for the system's operation can be agreed upon—including provisions for resolving questions or clarifying ambiguities. Experience suggests, however, that reaching such agreements can be a difficult and protracted process.

Even a modest subset of the measures outlined here could provide a degree of openness concerning weapon stockpiles and a framework for access to weapon sites that would greatly ease the difficulties of cooperation to improve security of nuclear weapons everywhere against theft or unauthorized use. For the more demanding purpose of monitoring agreements to control or reduce the stocks of nuclear weapons held by nuclear weapon states, the more intrusive measures would also be required.

Nuclear-Explosive Materials

Nuclear-explosive materials are readily convertible by nuclear weapon states (or other states or groups that have knowledge of nuclear weapon technology) into the nuclear-explosive components of actual weapons. And the size of the NEM stocks determines, to a reasonable approximation, how many weapons of particular types could be made. The difficulty of producing such materials means, moreover, that their acquisition is and will remain a limiting factor for states or subnational groups aspiring to make such weapons.

Applying transparency and monitoring measures to military and civilian stocks of NEM poses challenges that are comparable in overall difficulty with those of applying such measures to nuclear weapons, but different in some important respects. Accounting, management, control, and protection for NEM—the measures collectively referred to as MPC&A—are pursued by nations for both economic and security reasons and by the international community as part of the nuclear nonproliferation regime, and these efforts interact with transparency and monitoring in important and multifaceted ways. Transparency and monitoring are of limited value without competent MPC&A. Thus strengthening MPC&A, in addition to its direct benefits for security, is sometimes the most important step that can be taken toward improved transparency and monitoring. At the same time, improved transparency and monitoring can lead to identification and thus remedy of weaknesses in MPC&A. Increases in transparency and monitoring of NEM, if accepted, could also accelerate efforts to strengthen MPC&A through cooperative measures. Increased transparency, however, can also complicate the task of MPC&A by providing information useful to those who would steal NEM.

The work of the International Atomic Energy Agency (IAEA) has provided extensive multilateral experience with monitoring and transparency for civilian NEM and also some limited experience with military NEM. The United States and Russia have also acquired substantial bilateral experience through their cooperation to improve the security of Russian stocks of NEM, including joint work on technologies and methods for enhanced transparency and monitoring.

Transparency and monitoring measures for declared stocks of NEM at declared sites, comparable with those for nuclear weapons, could include:

- Comprehensive declarations describing the quantities and locations of all existing inventories of NEM, together with information on chemical forms and isotopic composition on the material;
- Declarations of inventories of NEM surplus to military and civilian needs; and
- Provisions for inspections of all declared facilities as well as of any undeclared suspicious activities.

As in the case of nuclear weapons, such "cooperative transparency" for NEM could be supplemented by information gathered unilaterally by individual states.

A number of additional measures could help to reduce the stocks and flows of NEM as well as to reduce the number of sites at which NEM are stored; all could be beneficial both in reducing the opportunities for theft and diversion and in easing the task of monitoring. The possibilities include:

- Accelerated disposition of excess Highly Enriched Uranium (HEU) inventories through down blending and eventual use in reactor fuel;
- Replacement of HEU fuels in research reactors with high-density low enriched uranium fuels, where feasible, and decommissioning of nuclear reactors using HEU fuels when replacement is not possible;
- Disposition of excess separated plutonium either by conversion to fuel for use in civil reactors or by immobilizing with fission products in a glass or ceramic matrix;
- A comprehensive cutoff of production of NEM for weapons;
- A serious international effort to develop nuclear fuel cycles for civil reactors that minimize or eliminate the exposure of NEM; and
- Centralization under multinational control of all facilities capable of enriching uranium or reprocessing plutonium.

Beyond the measures to reduce NEM stocks and flows and storage sites, two much broader efforts would provide great benefits for international efforts to increase transparency and monitoring for NEM:

1. Continued substantial improvements in national management, protection, control, and accounting of national holdings of NEM so that individual countries are fully aware of the quantity and status of all of their holdings of NEM and have provided effective protection against theft or diversion for all stocks of NEM; and
2. Continued efforts to strengthen the safeguards regime administered both bilaterally and by the IAEA, including universal applicability of the Additional Protocol, with increased manpower and funding to carry out the expanded mandate.

Important efforts to support both these goals are under way, but they should be enhanced and accelerated.

Greatly improved management and decreased inventories of NEM, which are priorities on their own account, would be critical if limits on total numbers of weapons were contemplated. The lower such limits became, moreover, the greater would be the need for reduction of NEM stockpiles and high confidence in monitoring the stocks that remained. While the technologies exist to achieve monitoring of NEM quantities with considerable accuracy and confidence under a cooperative framework, a strengthened international consensus on the value of doing this would be necessary to solve cooperatively the many difficult problems involved.

Clandestine Stocks and Covert Production

We have concluded that procedures and technology are available to verify with high confidence the declarations of stockpiles of nuclear weapons and NEM at declared sites. But undeclared nuclear weapons and NEM could exist as a consequence of retention of undeclared existing nuclear weapons and NEM or could come into existence by the clandestine production of nuclear weapons from existing NEM. In addition, undeclared NEM for weapons might be produced clandestinely or diverted covertly from peaceful nuclear power programs. Current non-nuclear weapon states and possibly terrorist groups might also acquire nuclear weapons or NEM. The potential for clandestine activities in these categories poses the largest challenges to efforts to strengthen transparency and monitoring for nuclear weapons, components, and materials on a comprehensive basis.

The public record of the ability of U.S. intelligence agencies to identify the emergence and evolution of the nuclear weapon programs of countries of interest in the past is one indication of the likelihood of future success in detecting covert programs. Historically, U.S. intelligence has become aware of the efforts by other countries to develop nuclear weapons relatively early in their programs and well in advance of their actually obtaining a weapon. Estimates of the date of the initial fabrication of an actual nuclear device and future inventories of materials and weapons have often underestimated or overstated actual capabilities, however. On the other hand, methods for detecting and evaluating clandestine efforts have been improving over time and should continue to do so.

The methods available for the detection of a clandestine effort to acquire a nuclear weapon capability include:

- A range of NTM, including real-time, high-resolution satellite photography and other satellite sensors. Satellite, ground-based, and sea-based receivers also collect a broad range of signal intelligence, the extent and quality of which is closely held information. While traditionally such intelligence collection is limited to sensors outside the borders or above the sensible atmosphere of the state being observed, sensors could also be located on or flown above the territory of a state subject to inspection as part of a formal agreement. The United States invests substantial resources in research and development to continue improving its already impressive NTM capabilities.
- Audits or inspections carried out as part of formal agreements. These measures, which can include the use of forensic techniques to reveal illicit alteration of records, may call attention to discrepancies or suspicious activities that suggest potential clandestine activity. Inspections can gather a variety of kinds of physical evidence, including forms amenable to use of the techniques of “nuclear archaeology” to help determine what a facility has actually produced over time.
- Human sources, including travelers, emigrants, defectors, “whistle-blowers,” and intelligence agents working within the institutions of a state engaged in illegal activities. Beyond the well-established value of these types of sources, the probability that individual citizens of a country would report to international authorities on activities that contravene treaties may be increased by requiring countries to pass domestic laws making it illegal for individuals to participate in such activities. Individual participation in or concealment of such activities could also be criminalized under international law.

The most difficult task is detection of clandestine stocks accumulated from past undeclared production or from materials transferred from other states. Independent knowledge of the actual total size of the Russian stockpiles of nuclear weapons and NEM, for example, is sufficiently uncertain that verified declarations alone cannot preclude the possibility that significant undeclared stockpiles might exist at undeclared locations. A similar situation exists with respect to the nuclear stockpiles of other nuclear weapon states with much smaller programs, where the absolute size of the uncertainty would be proportionately smaller. The declared NEM holdings by non-nuclear weapon states with peaceful nuclear programs also involve uncertainties, which would be smaller in the case of states whose nuclear programs had always been subject to international verification, but the possibility of some undeclared stocks could still not be entirely excluded. Small clandestine weapons fabrication facilities utilizing NEM obtained from an external source would be very difficult to detect. All of this underscores the importance of global accounting, monitoring, and protection for all NEM from past and future production.

The Nuclear Non-Proliferation Treaty (NPT) obligates non-nuclear-weapon-state parties to that treaty to conclude an agreement with the IAEA to safeguard civilian nuclear installations against diversion of NEM. In the past IAEA agreements have focused on declared facilities and have limited the authority of the IAEA in carrying out inspections. IAEA has now created an "Additional Protocol" that explicitly permits unannounced inspections of suspect undeclared facilities and adds many other intrusive constraining measures, but many states have not yet signed that document. If the Additional Protocol were universally enacted and were coupled with use of the best available monitoring technologies, the potential for illegal diversion of NEM from the declared peaceful programs of participating states could be reduced to a minimum level. Similarly, with effective approaches and adequate resources applied to the task, the peaceful nuclear energy programs of nuclear weapon states could be adequately monitored to reduce to a very low level the risk of undetected diversions by those states and by unauthorized personnel for transfer to proliferating states or terrorist groups.

Given the extensive knowledge of existing nuclear programs, the significant amounts of additional information that would result from the process of verifying declarations, the new inspection capabilities provided by the Additional Protocol, and above all the demonstrated capabilities of NTM, it is very unlikely that any state, including Russia, participating in a cooperative fashion involving detailed declarations could develop a complete, stand-alone covert nuclear weapon production program that would not be discovered over time. If, however, undeclared stocks of NEM exist or can be diverted without detection from civilian stocks or production facilities, then it is much more likely that the assembly of new weapons could escape detection.

GENERAL CONCLUSIONS

As a result of the assessments described above, we have come to the following general conclusions:

1. Current and foreseeable technological capabilities exist to support verification at declared sites, based on transparency and monitoring, for declared stocks of all categories of nuclear weapons—strategic and nonstrategic, deployed and nondeployed—as well as for the nuclear-explosive components and materials that are their essential ingredients. Many of these capabilities could be applied under existing bilateral and international arrangements without the need for additional agreements beyond those currently in force.

2. There are some tensions between sharing information about nuclear weapon and NEM stockpiles and maintaining the security of these stockpiles, but cooperative use of available and foreseeable technologies can substantially alleviate these tensions.

3. The nature of NEM production and the characteristics of NEM and nuclear weapons place some fundamental limits on the capabilities of any system of monitoring and transparency to provide assurance of compliance. Accordingly, a degree of uncertainty is inescapable.

4. The biggest challenge to the kinds of cooperation-based verification discussed here would arise if countries tried to give the appearance of cooperation while covertly retaining undeclared stockpiles of nuclear weapons or NEM and/or undertaking clandestine production programs. Where concerns about compliance exist, the synergistic effect of multiple technical and management measures, supported by increased transparency and robust national technical means of intelligence collection, could reduce the risk that significant clandestine activities would go undetected and over time could build confidence that verification was effective.

5. Important transparency measures for both nuclear weapons and NEM need not necessarily be imposed as part of formal treaties but could be undertaken on the basis of informal understandings or unilateral initiatives, for example, as part of broader confidence-building efforts.

6. There are both liabilities and benefits of seeking, in the long run, to incorporate measures governing transparency and monitoring of nuclear weapon and NEM stockpiles into formal agreements. The complexity and intrusiveness of the most ambitious measures mean that negotiation of such agreements may be difficult and protracted. But it is precisely the complexity and intru-

siveness of some of the relevant measures that, together with the national security stakes, make formal agreements useful to avoid misunderstandings and to provide mechanisms to clarify ambiguities. In addition, formal agreements provide more durable assurance that measures will be sustained over time and across changes in governmental leadership.

7. In the committee's judgment, the synergistic effect of the approaches discussed in Chapters 2, 3, and 4 in a cooperative environment, coupled with robust NTM capabilities, would substantially reduce current uncertainties in U.S. assessments of foreign nuclear weapon and NEM stockpiles over time. Nevertheless, in view of the sheer size and age of the Russian stockpile (where current uncertainties amount to the equivalent of several thousand weapons), Russia probably could conceal undeclared stocks equivalent to several hundred weapons. In the case of other countries with much smaller programs, absolute uncertainties would be much less, leading to the possibility that these countries could conceal undeclared stocks equivalent to one or two dozen weapons in the case of China, and at most one or two weapons in the cases of Israel, India, and Pakistan. Confidence that declarations were accurate and complete, and that covert stockpiles or production facilities did not exist, would be increased by the successful operation of a monitoring program over a period of years in an environment of increased transparency and cooperation.

1

Introduction

THE SCOPE OF THE STUDY

This study explores the extent to which current and foreseeable approaches to transparency and monitoring can support verification for all categories of nuclear weapons—strategic and nonstrategic, deployed and nondeployed—as well as for the nuclear-explosive components and materials that are their essential ingredients.[1] We believe that increasing the categories of items subject to transparency and monitoring would be valuable—and may ultimately be essential—as the United States and the world attempt to address the urgent and interrelated goals of reducing the dangers from existing nuclear arsenals, minimizing the spread of nuclear weaponry to additional states, and preventing the acquisition of nuclear weapons by terrorists.

In the specific case of reductions in existing nuclear arsenals, we believe that more comprehensive verification would almost certainly be deemed essential if the United States and Russia decided to pursue substantially deeper cuts in nuclear weaponry than those agreed in the Moscow Treaty of 2002. Extending agreed limits to nuclear weapon states with smaller arsenals (for example, China, France, and the United Kingdom among the *de jure* weapon states and India, Pakistan, and Israel among the *de facto* ones) would likewise increase the desirability if not the necessity of more comprehensive verification.

The motivation and scope for this study were not confined to understanding the transparency and monitoring possibilities and requirements germane to more ambitious arms control regimes. The study has also focused on potential applications to the continuing challenges of keeping nuclear weapons out of the hands of proliferant states and terrorists; for example, the United States has emphasized the need for verification in the complete elimination of

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[1] The specialized meanings intended here for “transparency,” “monitoring,” “verification,” and related terms are provided in Box 1-1.

North Korea's nuclear weapons program. Likewise, as the United States continues to work with Russia to ensure that nuclear materials are adequately protected and accounted for, the partners will continue to require transparency measures to facilitate the process, as has been the case in the implementation of the 1993 Highly Enriched Uranium Purchase Agreement.

The study has addressed the technical and institutional approaches and capabilities in transparency and monitoring that could be applied to any or all of these purposes. It has not tried to analyze or make recommendations about the choices in U.S. nuclear weapon and nonproliferation policies and priorities that will continue to shape the context within which such approaches and capabilities might be applied. The pros and cons of different policy choices in these domains have been and continue to be extensively explored both inside and outside of government,[2] and we did not want to detract from this study's primary focus on technical and institutional capabilities by revisiting this policy terrain here.

We address the challenges and possibilities of increased transparency and monitoring largely in the context of the U.S. and Russian arsenals of nuclear weapons and stockpiles of nuclear-explosive materials (NEM).[3] Those two countries have by far the largest inventories of nuclear weapons and NEM, and they also have the most extensive, varied, and sustained experience with the possibilities and pitfalls of transparency, monitoring, and verification. It is reasonable to assume that solutions to the problems of

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[2] For U.S. government policy statements see, for example, "The National Security Strategy of the United States of America" (Washington, DC: The White House, September 2002). Available as of January 2005, at: http://www.whitehouse.gov/nsc/nss.html and "National Strategy to Combat Weapons of Mass Destruction" (Washington, DC: The White House, December 2002). Available as of January 2005, at: http://www.whitehouse.gov/news/releases/2002/12/WMDStrategy.pdf. This committee's studies include Committee on International Security and Arms Control, *The Future of U.S. Nuclear Weapons Policy* (Washington, DC: National Academy Press, 1997) and Committee on International Security and Arms Control, *Management and Disposition of Excess Weapons Plutonium* (Washington, DC: National Academy Press, 1994). Bibliographies and links to other government and nongovernment publications may be found at a number of Web sites, in particular those of the Nonproliferation Project of the Carnegie Endowment for International Peace, available as of January 2005, at: http://www.ceip.org/files/nonprolif/default.asp and the Nuclear Threat Initiative, available as of January 2005, at: http://www.nti.org/e_research/e_index.html.

[3] A "nuclear-explosive material" is a mixture of fissionable nuclides in which the proportions of these are such as to support an explosively growing fission chain reaction when the material is present in suitable quantity, density, configuration, and chemical form and purity. Uranium containing more than 20 percent U-235 or more than 12 percent U-233 (or an equivalent combination of proportions of these two nuclides) is considered NEM, as are all mixtures of plutonium isotopes containing less than 80 percent Pu-238. See Chapter 3 and Appendix A for more detail.

transparency and monitoring presented by the U.S. and Russian situations, with appropriate adjustments, could be applied successfully to other situations.

The study attempts to assess qualitatively the degree of confidence that would be associated with implementation of the measures discussed. In making these assessments, the study first examines what could be accomplished if Russia and the United States, as well as other countries, undertook these measures in a cooperative fashion, meaning that the countries would agree to provide relevant information and permit monitoring of the types requiring cooperation, within limits governed by their perceived needs to protect information that could compromise their security or aid proliferators. The study then critically examines the implications of possible clandestine efforts to retain undeclared stocks or to produce weapons or NEM. This study does not address the serious issue of how to respond to clear violations of relevant agreements or treaties, since these are essentially political questions whose answers depend on the particular circumstances surrounding the events.

CONTEXT

Nuclear weapons are evidently deemed by the states that possess them to confer security benefits outweighing the costs and risks of acquiring and maintaining these arsenals. Similarly, states that have no nuclear weapon program but do possess stocks of NEM in connection with civil nuclear energy or research activities evidently believe the economic and scientific benefits of NEM possession justify the costs and risks of such possession. Whether or not one agrees with these judgments of net benefit, the size of the risks associated with the existence of nuclear weapons and the materials needed to make them clearly merit continuing review of how those risks might be reduced at acceptable cost.

The risks associated with the world's stockpiles of nuclear weapons, their nuclear-explosive components, and NEM include:

- the dangers in the potential for use of existing arsenals; these include the possibilities of deliberate use of nuclear weapons by their authorized possessors as well as the possibilities of accidental, inadvertent, or unauthorized use;
- the risks that the existing arsenals and perceptions about their characteristics and intended uses will provoke fur-

ther, potentially destabilizing nuclear weapon developments and deployments either by the countries already possessing such weapons or by additional countries; and

- the danger that the existing stockpiles of weapons, components, and NEM will be the enablers rather than merely one of the motivators of proliferation, through illicit transfer to or theft by (or on behalf of) proliferant states or terrorist groups.

These risks are exacerbated in many respects by the size of the current arsenals and by the magnitude of the stockpiles of NEM worldwide.

The United States and Russia possess about 95 percent of the approximately 30,000 existing nuclear weapons, with the remainder held by the United Kingdom, France, China, Israel, India, Pakistan, and possibly North Korea. Relevant stocks of NEM include not only the inventories in military programs but also NEM in research reactors and the increasing quantity of plutonium in civil nuclear power programs. Besides what is in actual nuclear weapons, enough additional NEM exists in military and civil nuclear facilities worldwide to make something like 100,000 additional nuclear weapons. These stockpiles of NEM, in addition to presenting a ready resource for further production of weapons by the states holding them, also constitute a potential source of materials that could be used for the fabrication of nuclear weapons by non-nuclear weapon states and even terrorist groups.

Minimizing the risks from nuclear weapons, components, and NEM requires a strategy employing multiple tools. This study has focused on the challenges and possibilities for applying transparency and monitoring more comprehensively than has been undertaken until now. But the study has given due attention to how these measures interact with the other tools being deployed simultaneously to reduce the panoply of risks from nuclear weapons.

For NEM as well as for nuclear weapons and their nuclear-explosive components, the problems of monitoring are linked in many ways to those of materials protection, control, and accounting, generally collectively referred to as MPC&A in the case of NEM. A country's internal management and record keeping of its own nuclear weapons and NEM, for example, are prerequisites for external transparency to be meaningful. If a country does not itself know its inventories of nuclear weapons and NEM and where they are, any transparency it provides to others will be of limited value.

Good internal control and accounting can greatly ease the task of external monitoring and increase the confidence derived from it.

If a country fails to provide adequate protection of its nuclear weapons and NEM against theft, all that will be achieved even by good accounting is to reveal to the country's leadership after the fact that a serious security breach has occurred; all that external transparency will achieve is to reveal the situation to other states. In this connection, it can be argued that excessive transparency about quantities and locations of NEM (as well as intact weapons and their nuclear-explosive components) could increase the challenge of providing adequate protection, just as too much transparency about numbers and locations of weapons could increase vulnerability.

At the same time, appropriate forms of transparency among countries relating to weapons and NEM could lead to the identification and correction of weaknesses in the protection, control, and accounting measures in the participating countries. The cooperation between the United States and Russia since the end of the Cold War on protection, control, and accounting for nuclear weapons and NEM, for example, has led to increased interest on the part of the two governments in at least limited forms of transparency relating to these activities, and also to advances in the development and application of improved approaches and technologies for achieving such transparency.

The specific timetables and measures for improving the management of nuclear weapons and NEM stockpiles will depend on the international political climate, which will determine both the security advantages and risks of diverse approaches. While there have been temporary setbacks, over time increasing transparency has become a more important and politically feasible tool for managing and limiting nuclear weapons and NEM inventories. Transparency measures can be passive; for example, the START I Treaty discussed below contains provisions prohibiting encryption of certain missile flight test data and providing limited access to certain sensitive facilities. Transparency measures can also be active; the START I Treaty requires regular exchanges of specific information and data on the numbers and types of delivery systems.

Any assessment of the benefits of specific increases in transparency, however, must be balanced against concerns about revealing sensitive information that could increase a nation's vulnerability or aid proliferators. Both the United States and Russia have moved slowly and cautiously to share information regarding even well-known aspects of their nuclear arsenals and remain reluctant to provide each other with information they regard as closely related to the details of weapons design. Countries with small nuclear arsenals would have greater concerns about sharing information regarding the location of their nuclear weapons.

HISTORICAL PERSPECTIVE

Most of the measures and technologies assessed in this study were developed in the course of continuing efforts to find ways to limit the destructive potential of nuclear arsenals and to prevent their proliferation, first to other countries and more recently to terrorist groups. Attempts to limit nuclear weapons have often been controversial, with the perceived utility of arms control and nonproliferation paralleling the ups and downs of U.S.-Soviet relations over the course of the Cold War and then the growing concerns with rogue states and terrorism in the post-Cold War period. Verification issues frequently have been at the heart of these controversies, with debates focusing on the likelihood of cheating and the capability to assess compliance in fundamentally adversarial relations. On a number of occasions, however, the bilateral or multilateral political will needed to increase transparency and the availability of suitable monitoring technologies for these purposes have allowed the completion of measures and agreements, including some previously thought unattainable.

Any assessment of the technical and institutional capabilities for monitoring and transparency takes place within this historical context of achievement and controversy. Box 1-2 provides a timeline with key dates in this 60-year nuclear history. The remainder of this section is organized around four aspects of nuclear risk reduction—limiting and reducing existing nuclear arsenals, preventing the spread of nuclear weapons to additional countries, limiting nuclear tests, and securing nuclear weapons and NEM—to illustrate how each has been affected by the possibilities and limitations of technologies and methods for transparency and monitoring rather than a chronological presentation.

Limiting Existing Nuclear Arsenals[4]

This study assesses the potential for applying monitoring and transparency arrangements to all types of nuclear weapons, to their nuclear-explosive components, and to NEM. Traditionally, however, nuclear weapons in themselves, once produced, have not been considered suitable candidates for direct, verified control under international agreements or unilateral initiatives because they are small, easily concealed, and cloaked in secrecy. The introduction in the early 1960s of reconnaissance satellites carrying high-resolution cameras and other sensors, as well as other National Technical Means (NTM), made it possible to monitor with confidence the numbers and types of strategic delivery systems. Counting strategic delivery vehicles (that is, missiles, missile launchers, and aircraft) became available as a surrogate for verifying the nuclear weapons themselves in determining and limiting the size of strategic nuclear forces. The maximum number of weapons that each type of land- or sea-launched ballistic missile was designed to carry could be determined from intercepts of telemetry of flight test data.

The new technical capabilities enabled the negotiation of the first strategic arms limitation agreements between the United States and the Soviet Union. Initial contacts began under President Johnson; the Strategic Arms Limitation (SALT I) Agreements, which consisted of an Interim Agreement on Strategic Forces setting temporary ceilings on intercontinental and submarine-launched ballistic missile (ICBM and SLBM) forces and the Anti-Ballistic Missile (ABM) Treaty of unlimited duration were negotiated under President Nixon and signed by him in 1972.[5] Of particular note for this study are two key developments in transparency and monitoring in both agreements:

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[4] For background, see Committee on International Security and Arms Control, National Academy of Sciences, *Nuclear Arms Control: Background and Issues* (Washington, DC: National Academy Press, 1985). Descriptions and texts of all the agreements discussed are available as of January 2005, at http://www.state.gov/t/ac/trt/.

[5] Satellite reconnaissance had revealed that the Soviet Union was constructing an ABM system around Moscow paralleling U.S. plans to deploy a nationwide ABM system, which led to a U.S. decisions to seek limits on both offensive and defensive forces to avoid sparking a further arms competition.

- Creation of a Standing Consultative Commission to provide an established venue to address issues of treaty compliance for both agreements; and
- Formal recognition of the use of NTM to provide assurance of compliance and commitments not to interfere with NTM and not to use deliberate concealment measures to impede verification with NTM.

Under President Ford, negotiations began on a SALT II Treaty to establish permanent ceilings on strategic aircraft as well as ICBMs and SLBMs. This treaty, which was completed under President Carter in 1979, specified in great detail the provisions for monitoring of strategic forces and limits on missile tests to control qualitative improvements in strategic forces. The Soviet invasion of Afghanistan, however, ended efforts to obtain Senate advice and consent to U.S. ratification of SALT II.

When President Reagan entered office, he initially rejected SALT II but soon came to espouse substantial reductions in strategic offensive nuclear forces. His approach to verification was summed up in his famous comment, “Trust but verify.” In 1982 the United States joined the Soviet Union in negotiations that sought to reduce the number of strategic delivery systems rather than setting future ceilings.

Although the first Strategic Arms Reduction Treaty (START) was not completed during President Reagan’s Administration, the Intermediate Range Nuclear Forces (INF) Treaty, which banned all Soviet and U.S. ground-based nuclear-armed missiles with ranges between 500 and 5,500 kilometers was completed in 1988. As discussed further in Chapter 2, the treaty broke new ground by requiring on-site monitoring of the destruction of all such missiles and their launchers. In addition, the relevant U.S and Soviet missile manufacturing plants were subject to continuous perimeter and portal monitoring, including x-ray examination of large containers leaving the plant to make sure that intermediate-range missiles were not being manufactured. The nuclear weapons themselves, however, could be returned to storage, and some may have been subsequently redeployed on permitted systems.

A year before the breakup of the Soviet Union, President George H. W. Bush signed the START I Treaty on July 31, 1991. The treaty set numerical limits on deployed strategic nuclear delivery vehicles (ICBMs, SLBMs, and heavy bombers). After a seven-year implementation period, each party could have no more than 1,600 delivery vehicles, corresponding to no more than 6,000 “accountable” weapons. The number of “accountable” weapons was determined by agreeing to allocate a certain number of weapons to each type of delivery vehicle.

START I includes numerous intrusive measures to assist verification, which are described further in Chapter 2. They included 12 types of on-site inspections and a number of provisions to facilitate verification by NTM, such as a commitment not to encrypt or impede access to telemetry on ballistic missile flight testing. Protocols spelled out in great detail the procedures for destroying treaty-limited items. The two sides exchanged detailed declarations, which have been updated every six months, on the numbers by types of strategic delivery vehicles and launchers. After full implementation, the agreement probably resulted in about a 40 percent reduction in the actual number of strategic nuclear weapons deployed by each side. Hundreds of on-site inspections have been successfully carried out under the START I and INF treaties, providing a substantial experience base to draw on for any future arms reduction efforts.[6] But no provisions required control or dismantlement of the nuclear weapons "retired" as a consequence of the agreements.

As concern rose in the early 1990s about the security of nuclear weapons with the impending collapse of the Soviet Union, the United States undertook unilateral initiatives on strategic and nonstrategic nuclear weapons to supplement the formal treaty process, calling on the Soviet Union to reciprocate and suggesting specific actions the Soviets could take.[7] On September 27, 1991 President Bush announced a number of major steps, including:

- unilateral withdrawal of all U.S. ground-based nonstrategic nuclear weapons to the United States, as well as the removal of all sea-based nonstrategic weapons and all nonstrategic weapons associated with land-based naval aircraft;
- dismantlement of all ground-based and about half of the sea-based nonstrategic nuclear weapons; and

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[6] For an official history of the INF inspection experience, see Joseph P. Harahan, *On-Site Inspections Under the INF Treaty* (Washington, DC: On-Site Inspection Agency, Department of Defense, 1993). Available as of January 2005, at: http://www.fas.org/nuke/control/inf/infbook/tabcon.html. Unfortunately, a similar official account of the START inspection experience is not yet available.

[7] "Presidential Initiative on Nuclear Arms" (Washington, DC: The White House, September 27, 1991). Available as of January 2005, at:
http://dosfan.lib.uic.edu/acda/factshee/wmd/nuclear/unilat/sandy.htm.

- removal of all U.S. strategic bombers from day-to-day alert and removal from alert all of the ICBMs scheduled for deactivation under START I.

President Gorbachev reciprocated the following week by announcing comparable de-alerting measures and withdrawal of all Soviet nonstrategic nuclear weapons to the territory of the Russian Republic from Eastern Europe and the other Soviet republics. He also announced that all nuclear artillery and ground-launched tactical missile weapons would be dismantled.

In January 1992 the new Russian President, Boris Yeltsin, reaffirmed Gorbachev's unilateral pledge and extended it to include the dismantlement of half of Russia's air-launched tactical nuclear weapons, half of its nuclear weapons for antiaircraft missiles, and one-third of its tactical sea-launched nonstrategic nuclear weapons. Although these unilateral declarations were not subject to verification, it appears that all nuclear weapons outside Russia were successfully repatriated. The informal nature of the Presidential Nuclear Initiatives means the U.S. government has not verified how completely the Russian dismantlement commitments have been met, but the United States and Russia have made declarations to each other concerning what fraction of the commitments have been completed.[8]

START I and its verification provisions were extended by START II, which was negotiated under President George H.W. Bush and signed by him on January 3, 1993, as one of the final acts of his presidency. The U.S. Senate ratified the treaty in 1996. START II was to have reduced further the limits on ICBMs, SLBMs, and heavy bombers, but again with no provisions requiring the destruction of the nuclear weapons made excess. After U.S. withdrawal from the ABM Treaty in December 2001, the Russian Duma formally withdrew its ratification of START II, which had never entered into force. The United States and the Russian Federation continue to observe the transparency and monitoring provisions of START I, which will remain in force until 2009.

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[8] For example, Gunnar Arbman and Charles Thornton cite Russian sources that the Russian leadership announced a schedule for the elimination of "naval warheads by 1995; antiaircraft missile warheads by 1996; nuclear mines by 1998; and, nuclear warheads of tactical missiles and artillery shells by 2000." See Gunnar Arbman and Charles Thornton, "Russia's Tactical Nuclear Weapons, Part I: Background and Policy Issues," Report No. FOI-R-1057-SE (Stockholm: Swedish Defense Research Agency, November 2003), p. 14. Available as of January 2005, at: http://www.cissm.umd.edu/documents/thorntonrussia.pdf.

After initial delays, Belarus, Kazakhstan, and Ukraine, the three former Soviet republics with strategic nuclear weapons deployed on their territories, were persuaded to return the former Soviet strategic nuclear weapons to Russia, to destroy their launching facilities, and to join the Nuclear Non-Proliferation Treaty (NPT) as non-nuclear weapon states. The safe transfer back to Russia of all of the Soviet nuclear weapons outside of Russia when the Soviet Union collapsed and the agreement of all the non-Russian states of the former Soviet Union to forswear permanently nuclear weapons required sustained high-level U.S. cooperation with Russia and the three other states. The Nunn-Lugar assistance programs and the HEU Purchase Agreement (see "Securing Nuclear Weapons and NEM" below) proved essential policy tools in achieving this goal. Although the United States did not participate in the verification of the end results, the subsequent dismantlement of these weapons in Russia was reportedly monitored by Ukrainian inspectors who were familiar with the weapons through their former role as Soviet officers.[9]

In the mid-1990s U.S. negotiators attempted to engage their Russian counterparts in negotiations aimed at directly controlling nuclear weapons in addition to delivery vehicles and, as discussed further in Chapters 2 and 3, they also proposed a broad range of transparency measures for weapons and NEM. Although the Russians initially rejected both these proposals, Presidents Clinton and Yeltsin at a summit meeting in Helsinki, Finland, in March 1997 nonetheless agreed to the framework for a START III Treaty that would reduce strategic nuclear forces to a level of delivery vehicles equivalent to 2,000-2,500 "actual" nuclear weapons, and would contain measures "relating to the transparency of strategic nuclear warhead inventories and the destruction of strategic nuclear war-

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[9] "The Russian Federation and Ukraine signed an Agreement on the Procedure for Movement of Nuclear Munitions from the Territory of Ukraine to Central Pre-Factory Bases … for the Purpose of Dismantling and Destroying Them, which gave Ukraine the right to send three-man observer teams to each of the serial production facilities in Russia to monitor the process of dismantlement of warheads removed from Ukraine. Under the agreement, Ukrainian observers are to be provided by MOD's 12 Main Directorate with records on nuclear warheads to be dismantled. Observers 'control step by step the dismantling of nuclear munitions into their component parts and their destruction, the extraction and dismantling of the charge [physics package].'" Oleg Bukharin and Kenneth Luongo, "Appendix 1: Warhead Transparency Chronology," *U.S.-Russian Warhead Dismantlement Transparency: The Status, Problems, and Proposals*, PU/CEES Report No. 314 (Princeton, NJ: Center for Energy and Environmental Studies, Princeton University, April 1999). Available as of January 2005, at: http://www.ransac.org/new-web-site/pub/reports/transparency.html.

heads…"[10] Due to disagreements over whether to amend the ABM Treaty, however, formal negotiation of START III never began.

The Administration of President George W. Bush has taken the position that detailed formal treaties unduly limit U.S. flexibility in the face of unknown future threats and are no longer necessary in the context of a new, nonadversarial U.S.-Russian relationship. President Bush initially proposed reductions of strategic offensive weapons below the START I levels by informal unilateral declarations. At President Putin's insistence, however, he agreed to a formal treaty, signed in Moscow in May 2002. The Moscow Treaty commits the United States and Russia to reduce their "operationally deployed" strategic offensive nuclear weapons to between 1,700 and 2,200 by the end of 2012. By agreeing to reductions in operationally deployed strategic offensive nuclear weapons, the Moscow Treaty makes nuclear weapons—as distinct from delivery systems and launchers—the critical security consideration. The treaty does not include reserve strategic nuclear weapons or non-strategic active and reserve weapons, however.[11]

President Bush broke with previous U.S. insistence on strict verification of all nuclear arms control agreements and the increasingly intrusive verification measures developed through the INF and START process—the Moscow Treaty contains no transparency or monitoring provisions to support verification. Instead, verification of the Moscow Treaty depends on NTM and the declarations and monitoring under START I, which unless extended will end in December 2009, three years before the United States and Russia are obligated to meet any of the reductions called for in the Moscow Treaty.

The Senate resolution of advice and consent to the Moscow Treaty, which passed on March 6, 2003, by a vote of 95 to 0, contained a number of conditions expressing concerns about the treaty's lack of verification procedures. The conditions *inter alia* require the President to report annually in detail on the implementation of the treaty, including any further agreements on verifica-

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[10] "Joint Statement on Parameters on Future Reductions in Nuclear Forces," (Washington, DC: The White House, Office of the Press Secretary, March 21, 1997). Available as of January 2005, at: http://www.nti.org/db/nisprofs/fulltext/treaties/abm/abm_heje.htm.

[11] Nonetheless, in testimony on the Moscow Treaty before the Senate Foreign Relations Committee on July 9, 2002, Secretary of State Colin Powell indicated that the total U.S. nuclear stockpile would be reduced to fewer that 5,000 weapons by 2012. Available as of January 2005, at: http://www.state.gov/secretary/rm/2002/11743.htm.

tion and transparency measures; encourage the President to continue strategic offensive weapons reductions "to the lowest possible levels consistent with national security…;" and urge the President to establish cooperative measures to provide mutual improved confidence in accurate accounting and security of nonstrategic nuclear weapons.[12]

In April 2003 Secretary of State Colin Powell affirmed to the 2003 Preparatory Committee Meeting for the 2005 NPT Review Conference that "the United States remains firmly committed to its obligations under the NPT. We are pursuing a number of avenues that promote the goal of nuclear disarmament. The Moscow Treaty and other U.S. actions are based on a desire and an intention to reduce our reliance on nuclear weapons and eliminate surplus stocks of weapons-grade material."[13] Similarly, in a report to Congress on implementation of the Moscow Treaty in March 2003, the State Department emphasized that while the treaty did not include verification measures because of the new relationship with Russia, this new relationship is expected to lead to "increasing openness," which will be "increasingly useful as the deadline for meeting the Treaty's central obligation approaches."[14] The United States and Russia have established a Consultative Group on Strategic Security, which includes three working groups, the first one of which is focused on transparency in strategic offensive force reductions. The working group has met several times, but no specific agreements on transparency measures have been announced.

Preventing the Spread of Nuclear Weapons[15]

Although early U.S. nuclear weapons policy focused on the immediate threat posed by the growing Soviet nuclear capability,

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[12] Senate advice and consent to the Moscow treaty is available as of January 2005, at: http://thomas.loc.gov/cgi-bin/ntquery/z?trtys:107TD00008.

[13] Message from U.S. Secretary of State Colin Powell to the 2003 Preparatory Committee Meeting for the 2005 NPT Review Conference, quoted by Assistant Secretary of State J.S. Wolf, "Remarks to the Second Meeting of the Preparatory Committee," April 28, 2003. Available as of January 2005, at: http://www.state.gov/t/np/rls/rm/20034.htm.

[14] See "Annual Report on Implementation of the Moscow Treaty, 2003" (Washington, DC: The State Department, 2003). Available as of January 2005, at: http://www.state.gov/t/ac/rls/or/25474.htm.

[15] For background, see Joseph Cirincione et al., *Deadly Arsenals: Tracking Weapons of Mass Destruction* (Washington, DC: Carnegie Endowment for International Peace, 2002).

concern also grew about the proliferation of nuclear weapons to other states. Controlling the spread required finding a balance with the widespread desire to exploit fully the peaceful applications of nuclear technology. With his Atoms for Peace initiative in 1953, President Eisenhower sought to contain proliferation by offering to assist other nations individually in their civilian nuclear power programs, provided they formally forswore the development of nuclear weapons. The International Atomic Energy Agency (IAEA) was thus organized in 1957 with the dual mission of promoting nuclear power and ensuring its restriction to peaceful purposes.

This balance served as the basis for negotiating the Nuclear Non-Proliferation Treaty, which was completed in 1968 under President Johnson and was ratified and entered into force in 1970 under President Nixon. Under its terms, the five states that had tested nuclear weapons by that time (the United States, Russia, the United Kingdom, France, and China) agreed not to help other countries acquire nuclear weapons. All other parties agreed not to acquire nuclear weapons but retained the "inalienable" right to pursue nuclear energy for peaceful purposes. In return, the nuclear-weapon states agreed to share peaceful nuclear technology and 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." As of early 2005 there were 189 states parties to the NPT; India, Pakistan, and Israel are not members, and North Korea announced its withdrawal from the treaty in January 2003.[16]

To verify compliance with their commitment the NPT requires signatory non-nuclear weapon states to negotiate safeguards agreements with the IAEA to confirm that their declared nuclear facilities and materials are used only for peaceful purposes, and to provide "timely warning" of any diversion of nuclear materials from peaceful programs. Throughout the 1990s a series of measures sought to strengthen IAEA safeguards following the discovery of the extent of Iraq's clandestine program after the Gulf War and revelations about North Korea's pursuit of nuclear weapons. In particular, a voluntary "Additional Protocol" was added to the traditional IAEA agreements giving the agency substantially greater

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[16] A list of current signatories may be found on the United Nations' Web site, available as of January 2005, at: http://disarmament.un.org:8080/TreatyStatus.nsf.

powers, including the explicit right to inspect suspected as well as declared facilities. As of early 2005 Additional Protocols were signed by 91 countries and were in force or being provisionally applied in 68 states. While they are in force in less than a third of the parties to the NPT, they include a large fraction of the NPT non-nuclear weapon states with major nuclear activities on their territory.[17] The Nuclear Suppliers Group, an informal committee that coordinates export policies on equipment and materials of potential significance to nuclear weapons programs, is actively discussing making acceptance of the Additional Protocol a condition of nuclear supply, as President Bush and the other leaders of the Group of Eight industrialized democracies have proposed.[18] The traditional and enhanced safeguards, which provide extensive multilateral experience with applying transparency and monitoring to civilian NEM and some limited experience with military stocks, are discussed in detail in Chapter 3.

The United States has sought additional ways to limit the proliferation of nuclear and other weapons of mass destruction (WMD). Secretary of Defense Les Aspin launched the "Defense Counterproliferation Initiative" in December 1993 to develop additional means to address these threats. In May 2003 President Bush announced the Proliferation Security Initiative (PSI) to create a coalition of states to undertake the interdiction on land, sea, or in the air of shipments of WMD, as well as missiles or other items that could be used to deliver or produce them, to terrorist groups or proliferant states. The 11 original PSI countries issued a statement of principles to govern their cooperation in September 2003, although they continue to emphasize that there is no formal organi-

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[17] See IAEA, "Strengthened Safeguards System: Status of Additional Protocols" (Vienna: International Atomic Energy Agency, June 16, 2004). Available as of January 2005, at: http://www.iaea.org/OurWork/SV/Safeguards/sg_protocol.html. 90 states have signed the protocol, as has Taiwan, which in IAEA practice does not count as a state. The figure of 68 includes 65 states where the protocol is in force; Taiwan, where it is also in force; and Libya and Iran, where it is being provisionally applied.

[18] President Bush: "I propose that by next year, only states that have signed the Additional Protocol be allowed to import equipment for their civilian nuclear programs. Nations that are serious about fighting proliferation will approve and implement the Additional Protocol." Text of President Bush's February 11, 2004 speech available as of January 2005, at: http://www.whitehouse.gov/news/releases/2004/02/20040211-4.html.

zation. As of late 2004 four other countries had joined the PSI coalition and some 60 others had voiced support.[19]

In April 2004 the United Nations Security Council approved a resolution to prevent non-state actors and terrorists from obtaining weapons of mass destruction.[20] Resolution 1540 declares that states shall abstain from supporting and must "adopt and enforce appropriate effective laws" to prohibit non-state actors from attempting to "manufacture, acquire, possess, develop, transport, transfer or use nuclear, chemical, or biological weapons and their means of delivery, in particular for terrorist purposes." Resolution 1540 also tasks states to develop domestic programs to secure and control nuclear, chemical, and biological weapons and their delivery devices. States must implement:

1. "effective measures to account for and secure such items in production, use, storage or transport";
2. "effective physical protection measures";
3. "effective border controls and law enforcement efforts to detect, deter, prevent and combat…the illicit trafficking and brokering in such items"; and
4. "effective national export and trans-shipment controls over such items."[21]

Limiting Nuclear Tests[22]

It is technically possible for a state and even a terrorist group with access to NEM to build a simple nuclear weapon similar to

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[19] In addition to the United States, the original members were Australia, France, Germany, Italy, Japan, the Netherlands, Poland, Portugal, Spain, and the United Kingdom. Canada, Norway, Russia, and Singapore have joined subsequently. See "The Proliferation Security Initiative (PSI) At a Glance," Fact Sheet (Washington, DC: Arms Control Association, June 2004). Available as of January 2005, at: http://www.armscontrol.org/factsheets/PSI.asp.

[20] See "Security Council Decides All States Shall Act to Prevent Proliferation of Mass Destruction Weapons. Resolution 1540 (2004)," United Nations Security Council Press Release, 4956th Meeting (PM). Available as of January 2005, at: http://www.un.org/news/press/docs/2004/sc8076.doc.htm.

[21] See United Nations Security Council Resolution 1540 (2004) Adopted by the Security Council at its 4956th meeting, on 28 April 2004. Available as of January 2005, at: http://domino.un.org/UNISPAL.NSF/0/bc94a057247ad11085256e8500541fe5?OpenDocument.

[22] For the early history, see Committee on International Security and Arms Control, National Academy of Sciences. *Nuclear Arms Control: Background and Issues* (Washington, DC: National Academy Press, 1985).

the one dropped on Hiroshima and to be confident that it will produce an explosive yield even if it has not been tested.[23] States seeking more advanced designs, however, would almost certainly need to test to be sure that the weapons would perform as designed. Limits on nuclear testing therefore became an early avenue to seek limits on both the "horizontal" and "vertical" proliferation of nuclear weapons.[24] Limits were also advocated in response to the health and environmental effects of nuclear weapons tests, especially those conducted in the atmosphere. President Eisenhower initiated negotiations on a Comprehensive Test Ban Treaty (CTBT) in 1958 with the Soviet Union and the United Kingdom with the goal of stopping the U.S.-Soviet race to build ever more powerful thermonuclear weapons. The key technical issue in the negotiations was the need for on-site inspections to verify compliance with a ban on all types of nuclear testing.

The negotiations, which engaged senior scientists from the United States, the United Kingdom, and the Soviet Union, collapsed in 1960 in the aftermath of the shooting down of a U.S. spy plane over the Soviet Union. When negotiations resumed under President Kennedy, the parties still could not reach agreement on the number and modalities of on-site inspections. The three countries did agree in 1963 on the Limited Test Ban Treaty, which banned all nuclear explosive tests except those completely contained underground. This eliminated the need for on-site inspections because atmospheric testing could be detected with confidence by other means outside national territory. A subsequent agreement, the Threshold Test Ban Treaty of 1974, limited the yield of underground tests to 150 kilotons, which at the time was considered the minimum yield that could be identified with confidence without on-site monitoring or inspections.

Efforts to improve the technical possibility of monitoring and verifying underground nuclear explosions led to cooperation between the United States and the Soviet Union in the 1980s. At a

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[23] National Academy of Sciences. *Technical Issues Related to the Comprehensive Nuclear Test Ban Treaty* (Washington, DC: National Academy Press, 2001). See also Matthew Bunn and Anthony Wier "Myth 3:Terrorists Could not Make a Nuclear Bomb if They Had the Material (Or Set Off a Bomb if They Had One)," *Securing the Bomb: An Agenda For Action* (Washington, DC: Nuclear Threat Initiative and the Project on Managing the Atom, Harvard University, May 2004), pp. 17-25. Available as of January 2005, at: http://www.nti.org/e_research/analysis_cnwmupdate_052404.pdf.

[24] "Horizontal" proliferation refers to the spread of nuclear weapons to additional states, while "vertical" proliferation refers to existing nuclear-weapon states acquiring more advanced weapons.

summit in Washington, DC in December 1987, the two countries agreed to use a method similar to the previously demonstrated U.S. CORRTEX[25] methodology in a set of on-site reciprocal experiments to monitor nuclear explosions at their corresponding test facilities. This culminated in the Joint Verification Experiments (JVE) where Soviet experts monitored a nuclear explosion at the Nevada Test Site on August 17, 1988, and U.S experts monitored a nuclear explosion at the Semipalatinsk test site on September 14, 1988.

The JVE's demonstration of the feasibility of the methodology led to the creation of a new verification protocol for the TTBT, which entered into force in December 1990. This set of agreements codified the use of the data collection systems demonstrated in the joint experimental tests, and required on-site verification by hydrodynamic data collection for nuclear tests over 35 kilotons. The JVEs laid the foundation for future technical cooperation between Russian and American scientists.[26]

At the 25th Anniversary Review Conference of the NPT in 1995, a renewed commitment by the five nuclear weapon states to reduce their nuclear arsenals was a critical element in achieving the necessary consensus for extending the treaty indefinitely beyond its original 25-year lifespan. The achievement of a CTBT was frequently cited as a litmus test of the willingness of the nuclear weapon states to reduce their dependence on nuclear weapons.[27]

The United States played a leading role in the successful multinational negotiation of a CTBT, which was signed in 1996 by the United States, Russia, China, the United Kingdom, and France. The treaty banned all nuclear tests in all environments and established an international organization for verification with detailed provisions for elaborate on-site inspection of suspicious events. In 1999 the Senate failed to approve the U.S. ratification that is

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[25] On March 14, 1986, President Reagan invited Soviet scientists to monitor a U.S. nuclear test using the CORRTEX (Continuous Reflectometry Radius versus Time Experiment) system, a method of directly measuring hydrodynamic data to permit direct estimates of yield and thereby resolve existing regional uncertainties resulting from teleseismic measurements. Information on CORRTEX is available as of January 2005, at: http://65.104.119.204/cas.html.

[26] For a Russian perspective on the contributions of the JVEs see National Research Council, *Overcoming Impediments to U.S.-Russian Cooperation on Nuclear Nonproliferation: Report of a Joint Workshop* (Washington, DC: The National Academies Press, 2004), Appendix D, pp. 71-72.

[27] 1995 NPT review conference Web site available as of January 2005, at:
http://disarmament.un.org:8080/wmd/npt/1995nptrevconf.html.

needed, along with ratification by other nuclear-capable states, for the treaty to enter into force. Much of the Senate debate turned on issues related to whether a CTBT could be verified and how much states possessing or aspiring to nuclear weapons could accomplish in the absence of testing, which were assessed in an earlier technical study conducted under the auspices of this committee and are not addressed further in this study.[28]

Securing Nuclear Weapons and NEM[29]

With the collapse of the Soviet Union, the United States and Russia recognized their common interest in ensuring the security of the nuclear warheads and NEM that had been part of the vast Soviet nuclear complex. The passage of the Nunn-Lugar legislation in late 1991 began an unprecedented series of initiatives under the general rubric of "cooperative threat reduction" (CTR). Under this rubric, a broad range of programs have been undertaken to secure, dismantle, and prevent proliferation of nuclear, chemical, and biological stockpiles or materials. The Department of Defense has provided financial and technical support for the denuclearization of Belarus, Kazakhstan, and Ukraine, and for the implementation of the START I agreement. By the mid-1990s, programs focused on cooperative threat reduction were being implemented by the departments of Energy and State as well.

With respect to the agenda of controlling nuclear weapons and materials covered in this report, current programs can be divided into six main categories: (1) securing and accounting for nuclear warheads and NEM (including upgrading security and accounting at existing sites, consolidating stockpiles at smaller numbers of buildings and sites, improving transport security, and upgrading national-level regulatory and accounting systems); (2) interdicting nuclear smuggling; (3) stabilizing employment of nuclear personnel, to reduce the risk that unemployed or underpaid personnel will steal NEM or sell nuclear secrets; (4) monitoring nuclear stockpiles and reductions; (5) ending further production of NEM; and (6) reducing stockpiles of surplus NEM.

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[28] National Academy of Sciences. *Technical Issues Related to the Comprehensive Nuclear Test Ban Treaty* (Washington, DC: National Academy Press, 2001).

[29] For comprehensive and regularly updated analyses of programs in these areas, with annotated links to other information available on the Internet, see the Web site maintained for the Nuclear Threat Initiative by Matthew Bunn and Anthony Wier, Controlling Nuclear Warheads and Materials available as of January 2005, at: http://www.nti.org/cnwm.

Programs in these areas have made notable progress. Thousands of nuclear weapons have been retired, enough HEU for thousands of nuclear weapons has been converted to low enriched uranium (LEU), and thousands of nuclear weapons and enough NEM for thousands more is demonstrably better secured today than it was a decade ago. U.S. and Russian experts are now cooperating to improve security and dismantle stockpiles at dozens of sensitive nuclear sites across Russia, including nuclear warhead storage facilities and major nuclear weapons complex facilities, a situation that would have been hard to imagine before the Soviet collapse. Nonetheless, across a broad spectrum of these efforts, much remains to be done, and a range of bureaucratic, political and financial problems—including particularly secrecy and the issue of access to sensitive sites—at the heart of the issues discussed in this report continue to slow progress.[30]

One particularly notable initiative is the U.S.-Russian HEU Purchase Agreement, signed in 1993, under which the United States agreed to purchase over a period of 20 years, for an estimated $12 billion, some 500 tons of Russian HEU from dismantled weapons down-blended by Russia to LEU, suitable for use in power reactors but not nuclear weapons.[31] Over the past 10 years, problems resulting largely from the U.S. decision in the mid-1990s to privatize the previously government-operated uranium enrichment industry slowed and even at one stage imperiled implementation of the deal. Nevertheless, by the end of 2004, just over 230 tons of Russian HEU had been down-blended to LEU; and the deal is now proceeding at a rate of about 30 tons of HEU per year.[32] The HEU Purchase Agreement has also been the principal area where formalized transparency measures have been successful, with transparency measures in place to confirm that the LEU delivered to the United States comes from HEU, and to provide at least modest confidence that the HEU in turn came from nuclear weapons.

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[30] For a discussion of key impediments to progress, see National Research Council, *Overcoming Impediments to U.S.-Russian Cooperation on Nuclear Nonproliferation: Report of a Joint Workshop* (Washington, DC: The National Academies Press, 2004).

[31] Throughout this report "ton" refers to metric tons. One metric ton is 2,205 pounds, roughly 10 percent more than an English ton.

[32] *Progress Report: U.S.-Russian Megatons to Megawatts Program*: *Recycling Nuclear Warheads into Electricity* (USEC, September 30, 2004). Available as of January 2005, at: http://www.usec.com/v2001_02/HTML/Megatons_status.asp.

These cooperative initiatives have created a substantial amount of informal transparency related to nuclear weapon and material stockpiles. The United States today has far more detailed knowledge of the totality of nuclear activities in Russia than it did 15 years ago. Similarly, as a result of unilateral U.S. openness initiatives and reciprocal visits undertaken as part of these programs, a great deal of information about U.S. nuclear activities has been made available to Russia and to others.[33]

Since the mid-1990s, U.S. and Russian technical experts have been pursuing joint lab-to-lab development of technologies that could be applied to confirming warhead dismantlement and monitoring warhead and NEM stockpiles, an effort that has taken on a focus on detection of explosives and nuclear materials for counterterrorism purposes since the September 11th attacks.[34] While these efforts have been successful in a technical sense and in creating a base of experience in working jointly on problems, none of the measures developed has been implemented in actual transparency or monitoring arrangements.

Secrecy and restraints on access to sensitive facilities remain difficult problems and are slowing these cooperative programs. Efforts to reach agreement on more formal transparency measures have been much less successful, moreover. Neither the United States nor Russia has verified the dismantlement of any nuclear weapons by the other party. Tentative accords reached in the mid-1990s to exchange data on warhead and nuclear material stockpiles, and to exchange inspections of storage facilities for excess nuclear materials, have never come to fruition, and have since been abandoned. As of early 2005, negotiations of transparency measures for the Mayak Fissile Material Storage Facility built in Russia with U.S. assistance had abandoned all the most intrusive measures the United States had once sought, but had still not led to agree-

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[33] For a discussion of some of these formal U.S.-Russian transparency efforts, see James Goodby, "Transparency and Irreversibility in Nuclear Warhead Dismantlement," in Harold A. Feiveson, ed., *The Nuclear Turning Point: A Blueprint for Deep Cuts and De-Alerting of Nuclear Weapons* (Washington, DC: Brookings Institution, 1999). See also Oleg Bukharin and Kenneth Luongo, *U.S.-Russian Warhead Dismantlement Transparency: The Status, Problems, and Proposals*, PU/CEES Report No. 314 (Princeton, NJ: Center for Energy and Environmental Studies, Princeton University, April 1999). Available as of January 2005, at: http://www.ransac.org/new-web-site/pub/reports/transparency.html.

[34] A useful summary of the work conducted in the lab-to-lab transparency technology development effort can be found in U.S. Department of Energy, Office of Nonproliferation and Nuclear Security, *Warhead and Fissile Material Transparency Program Strategic Plan* (Washington, DC: Department of Energy, May 1999).

ment, despite the completion of the facility. U.S.-Russian-IAEA discussions of the "Trilateral Initiative" for IAEA verification of excess NEM in the United States and Russia are not making progress, after having developed the technical and legal means to implement such an approach. Very limited monitoring of plutonium produced after the signature of the U.S.-Russian agreement to shut down Russia's plutonium production reactors has only begun in recent years, after years of difficult discussions and delays. And there has been no significant progress in implementing the transparency measures for disposition of plutonium in the 2000 U.S.-Russian Plutonium Management and Disposition Agreement.

Since the September 11th attacks, the Bush Administration and the U.S. Congress, working with international partners, have sought to accelerate the pace of securing these stockpiles, and broaden the threat reduction effort to include countries beyond those of the former Soviet Union. In June 2002 the Group of Eight (G8) industrialized democracies launched a $20 billion "Global Partnership Against the Spread of Weapons and Materials of Mass Destruction," in which the other members of the G8 pledged collectively to match the U.S. investment of roughly $1 billion per year in threat reduction over the ensuing 10 years.[35] The U.S. Congress, following the September 11th attacks, provided hundreds of millions of dollars in supplemental funding for efforts to secure nuclear and radiological materials, and has also authorized the administration to spend a portion of available threat reduction funds wherever in the world they may be needed, not only in the former Soviet Union.[36] Similarly, the IAEA has established a Nuclear Security Fund, substantially increasing the pace and scope of its efforts to help member states ensure that nuclear and radiological materials and facilities are not vulnerable to thieves and terrorists.[37] The United States and Russia have stepped up the pace of returning potentially vulnerable HEU that they supplied to facilities around the world. In May 2004 U.S. Secretary of Energy

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[35] For regularly updated information on the Global Partnership, see the Web site of the Strengthening the Global Partnership Project, led by the Center for Strategic and International Studies, available as of January 2005, at: http://www.sgpproject.org.

[36] See Anthony Wier, "Legislative Update," Overview and Budget. Available as of January 2005, at: http://www.nti.org/e_research/cnwm/overview/legislative.asp.

[37] For a discussion, see International Atomic Energy Agency, "Promoting Nuclear Security: IAEA Action Against Terrorism" (Vienna: IAEA, June 1, 2004). Available as of January 2005, at: http://www.iaea.org/NewsCenter/Features/NuclearSecurity/terrorism.html.

Spencer Abraham announced a Global Threat Reduction Initiative, intended to secure or remove the materials posing the highest proliferation threats around the world as quickly as possible.[38]

APPROACHES TO IMPLEMEMTING TRANSPARENCY AND MONITORING MEASURES

The choice of the means to implement the various combinations of transparency and monitoring measures described above have included a range of political processes, involving varying degrees of comprehensiveness, formality, and legal commitment. The choices are generally determined far more by political than technical factors, although as discussed above technological advances have sometimes made it possible to undertake more ambitious tasks than previously believed feasible.

- **Unilateral initiatives** may be undertaken for national reasons or be designed to encourage reciprocal actions. The Presidential Nuclear Initiatives in the early 1990s to return U.S. and Soviet/Russian nonstrategic nuclear weapons to the United States and Russia and to eliminate many of them are examples of the latter approach. Unilateral initiatives offer significant advantages in flexibility and the ability to move quickly in the face of rapidly changing conditions, but in the absence of formal monitoring or verification they may do little to reduce uncertainties.
- **Informal understandings** may offer the opportunity to explore new or innovative approaches, or enable countries to take actions that they might not yet be able politically to undertake formally, or provide the basis for bilateral actions where the relationship is sufficiently strong that more formal agreements are not needed. They do not, however, provide a formal basis for resolving differences that may emerge in implementation. In the early days of the U.S.-Russian cooperation on MPC&A such understandings enabled initiatives to be undertaken and progress to be made in the absence of more formal arrangements.

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[38] See Abraham's announcement at the IAEA on May 26, 2004. Available as of January 2005, at: http://www.energy.gov/engine/content.do?PUBLIC_ID=15949&BT_CODE=PR_SPEECHES&TT_CODE=PRESSRELEASE.

- **Executive agreements** are formal undertakings between governments that legally bind the parties but lack the full status of treaties; in the United States, for example, they require only a majority vote in the Congress or necessary implementing legislation. They are frequently undertaken to allow bilateral activities to take place, including the implementation of treaties (see below), and can be negotiated between specific ministries or agencies. The Cooperative Threat Reduction programs between Russia and the United States, for example, generally operate under executive agreements.
- **Treaties**, either bilateral or multilateral, are formal undertakings that the parties are expected to fulfill unless events endangering their "supreme national interests" lead to withdrawal. A treaty implies a commitment intended to extend beyond changes in leadership or governments. Successful treaties can provide a stable and predictable environment that enables states to take long-term actions that they would only be willing to contemplate in such a formal relationship. Treaty commitments, however, may also (sometimes deliberately) constrain flexibility and limit policy choices, and outmoded provisions may be difficult to adapt to new conditions. The desire for a means to gain some level of confidence about compliance with agreements has led to the formalization of monitoring and verification under treaties. The United States and the Soviet Union/Russia, for example, have relied on treaties for most of their arms control agreements.
- Measures pursued in a cooperative fashion generally involve continuous communication or **consultation** among the parties at a number of levels. In some cases, formal arrangements are created to facilitate consultation or to ensure that it takes place on a regular basis. A standing commission such as the one created for the 1972 ABM Treaty may serve as the venue to establish detailed procedures not included in a treaty, to interpret implementation provisions of a treaty or other agreements, and to attempt to resolve questions of compliance.
- The most ambitious process is a **regime**. In this case, a number of arrangements, which usually develop over time, collectively address a particular objective. The

> nuclear nonproliferation regime is the primary example in international security, with a core treaty (the NPT) supported by a variety of formal and informal arrangements. These include the IAEA with its formal bilateral safeguards agreements with all parties, the informal Zangger Committee and the London Suppliers' Group dealing with export control, and a number of regional treaties establishing nuclear-weapon-free zones. Any effort to address comprehensively the problems of monitoring and verifying stockpiles of nuclear weapons and NEM, bilaterally or eventually internationally, would almost certainly be developed as a regime.

THE STUDY

In the following chapters the study explores the availability and effectiveness of measures and technologies that could be used to monitor and verify nuclear weapons arsenals, including all weapons, weapons components, and NEM.

- Chapter 2 explores the technologies and processes that could be used to monitor and verify numbers of nuclear weapons and nuclear weapon components. Methods will be considered for making and confirming declarations and for monitoring the elimination of nuclear weapons and the fabrication of new weapons as replacements.
- Chapter 3 explores technologies and processes that could be used to improve transparency, monitoring, and verification for NEM associated with both military and civil nuclear programs, including measures to reduce the stocks and flows, and to undertake disposal of NEM.
- Chapter 4 assesses the problems of covert retention of undeclared nuclear weapons and NEM and future undeclared clandestine production of nuclear weapons and NEM.
- Chapter 5 draws on the findings of Chapters 2 through 4 to arrive at some overarching conclusions.

BOX 1-1

Specialized Terms

In this study a number of terms are used in special contexts.

Verification defines the process of determining compliance or noncompliance with an agreement—or the accuracy of a declaration—based on analysis of the totality of information available from all sources.

Monitoring includes all activities conducted to gather information on the status of nuclear weapons and nuclear weapons associated facilities—whether declared or undeclared and whether subject to an agreement or not—including agreed multilateral technical means, National Technical Means, inspections, and other sources of information.

- **Multilateral technical means** refers to information gathering and analytical capacities deployed by multinational bodies; for example, the IAEA currently deploys instrumentation, inspectors, and analytical capabilities related to the agency's responsibilities under the NPT and associated agreements.
- **National Technical Means (NTM)** covers all nationally operated technical collection activities located outside the territory of a state under observation (including the space above its sensible atmosphere) capable of gathering information concerning that state's compliance with an agreement.
- **Inspections** cover formal visits by inspectors representing another government or international institution to a declared facility or suspect activity, or the permanent stationing of inspectors at a declared facility. Inspectors can employ agreed technical equipment or install agreed permanent surveillance equipment.
- **Other sources** include open sources (newspapers, the Internet, historical documents and published technical papers), reports by travelers and defectors, "whistle blowers," and clandestine human sources.

Transparency describes an action or series of actions a state may take either unilaterally or by agreement to facilitate monitoring through the provision of information or access. Such transparency may apply only to specific other countries or international organizations or, alternatively, may include making information publicly available

Cooperation reflects the degree to which a state facilitates monitoring activities directed at its nuclear program in a problem-solving spirit as opposed to an overly legalistic approach or one involving active emplacement of obstacles in the way of monitoring and transparency.

Confidence in compliance with an agreement, accuracy of a declaration, or the absence of given categories of weapons, materials, or activities not covered by agreements or declarations is based on the results of monitoring activities and the perceived adequacy of those activities in relation to potential avenues of evasion and deception.

Strategic and **nonstrategic** nuclear weapons are categories based on the capabilities and intended uses of such weapons and their delivery vehicles. The distinctions are complicated and sometimes not useful. In this study, we simply use "strategic" to refer to the categories of weapons covered by past strategic arms control agreements between the United States and the Soviet Union/Russia (i.e., weapons matched to intercontinental ballistic missiles, submarine launched ballistic missiles, and long-range bombers) and we use “nonstrategic” for all others.

BOX 1-2

Key Dates in Nuclear History

July 16, 1945	First U.S. nuclear test
August 1945	United States drops atomic bombs on Hiroshima and Nagasaki
1946	Baruch Plan introduced at the United Nations
1949	First Soviet nuclear test
1952	First British nuclear test
1952-53	First U.S. and Soviet thermonuclear tests
1953	Atoms for Peace plan proposed by President Eisenhower
1957	Establishment of the International Atomic Energy Agency
1958	Official technical discussions on verifiability of a Comprehensive Test Ban Treaty (CTBT) by Scientists from the United States and Soviet Union and their allies; beginning of formal U.S., U.K. and Soviet negotiations on a CTBT
1960	First French nuclear test
1963	Limited Test Ban Treaty signed
1964	First Chinese nuclear test
1968	Nuclear Non-Proliferation Treaty signed
1972	SALT I and ABM treaties signed
1974	Indian “peaceful nuclear explosion”

1974	Threshold Test Ban Treaty signed
1976	Peaceful Nuclear Explosions Treaty signed
1979	SALT II signed
1987	INF Agreement signed
1991	START I signed
1991-92	Presidential Nuclear Initiatives by Presidents Bush, Gorbachev, and Yeltsin
1991	First Nunn-Lugar legislation passed
1993	HEU Purchase Agreement signed
1993	START II signed
1995	International agreement for indefinite extension of the NPT
1996	Comprehensive Nuclear Test Ban Treaty signed
1998	Indian nuclear tests and first Pakistani nuclear tests
1999	U.S. Senate refuses consent to ratification of CTBT
2001-02	United States withdraws from the ABM Treaty and Russia withdraws its ratification of START II
2002	Treaty of Moscow signed
2003	North Korea announces its withdrawal from the NPT

2

Nuclear Weapons

Transparency and monitoring measures can be employed at several phases in the life cycle of nuclear weapons, which is illustrated schematically in Figure 2-1. As discussed in Box 2-1, the key components of a nuclear weapon are those containing nuclear-explosive materials (NEM).[1] These components, together with high-explosive assemblies and various electrical and mechanical components, are assembled into nuclear weapons in specialized facilities; in the United States, this is done at the Pantex plant in Amarillo, Texas. Assembled weapons are transported to military storage facilities, where they are stored pending deployment with a delivery vehicle. Nuclear weapons are operationally deployed and ready for use when they are mated to ballistic missiles and placed in launchers, loaded onto aircraft, or stored at air bases for nuclear-capable aircraft.[2] Nuclear weapons may be removed from operational deployment from time to time for inspection and routine maintenance of the weapon or its delivery vehicle and launcher. Weapons also may be kept in long-term storage as spares, as a source of parts for remanufacture or the manufacture of other weapons, or held in reserve as a responsive force that may augment deployed forces. When a decision is made to eliminate a nuclear weapon, it is disassembled and the NEM components are stored for reuse or final disposition.

Past and current arms control agreements kept most of the nuclear weapons life cycle closed to outside scrutiny. As discussed in Chapter 1, nuclear weapons were not considered suitable for direct monitoring and transparency because of their small size, the ease with which they could be concealed, and the secrecy that sur-

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[1] NEM are defined in Footnote 3 of Chapter 1; see also Chapter 3 and Appendix A for a further technical discussion.

[2] This applies to gravity bombs and weapons for ballistic or cruise missiles, which account for the vast majority of the world's operational nuclear arsenals. In the past, the United States and Russia deployed other types of nuclear weapons, including landmines, artillery shells, depth charges, and weapons for air-defense missiles and torpedoes. In 1991-92 both sides pledged to withdraw from deployment these types of weapons and to dismantle all nuclear landmines, artillery shells, and weapons for short-range missiles (see Chapter 1). The United States has dismantled all of these other types of weapons; Russia may have air-defense and antisubmarine weapons in storage. China may stockpile some of these other types of nuclear weapons.

rounded them. For the most part, therefore, transparency and monitoring measures extended only to delivery systems (ballistic missiles and their silos, mobile and submarine launchers, strategic bombers, and cruise missiles). Agreed limits on the number of deployed strategic weapons were verified indirectly with counting rules that attributed a certain number of weapons to each deployed delivery system of a particular type. The first Strategic Arms Reduction Treaty (START I), for example, provides for a small number of inspections each year to confirm that the number of weapons on a selected ballistic missile does not exceed the number allowed for that type of missile. There have been no agreed limits on the number of strategic nuclear weapons that can be kept in storage for possible deployment, no declarations or measures to confirm the number of strategic or nonstrategic weapons in the stockpile, and the only measures to confirm that nuclear weapons have been eliminated are those being undertaken in connection with agreements concerning the disposition of highly enriched uranium from dismantled weapons.

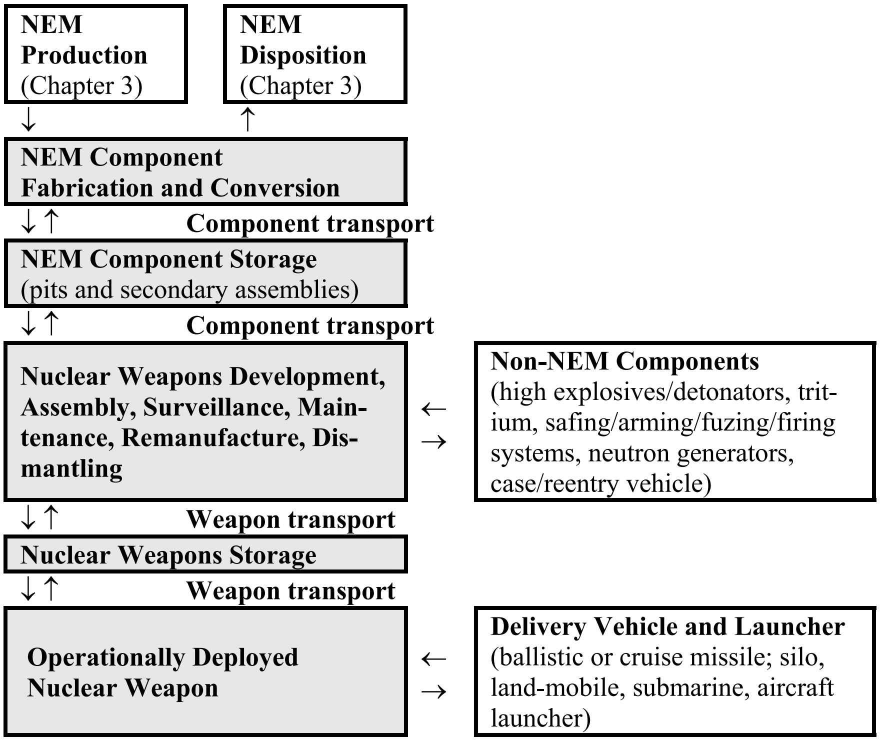

FIGURE 2-1 Life cycle of a nuclear weapon.

This chapter considers several possible measures for transparency and monitoring of nuclear weapon stockpiles. Chapter 3 then considers measures to apply transparency and monitoring to stockpiles of NEM, including current and past production in military and civilian programs and for the disposition of existing and future stocks. The measures related to nuclear weapons stockpiles include declarations of weapon inventories at various levels of detail; on-site inspections and other methods to confirm the accuracy of declarations disaggregated by facility; continuous monitoring of certain weapon stocks, such as excess or retired weapons in storage; transparency measures at weapon assembly facilities to confirm the dismantling and permitted remanufacture of weapons; and declarations and transparency measures covering the storage and fabrication of NEM components (pits and secondary assemblies; see Box 2-1 for an explanation of these terms). Other confidence-building measures that could prove useful include exchanges of information on historical weapon inventories including past assembly and disassembly records, facility design information and operating records, and other records. The various technologies available to support these measures are described and assessed in boxes; the chapter text describes how they might be applied.

The various measures are presented as an integrated package of progressively more demanding steps. We emphasize, however, that some are less sensitive and intrusive and could have value as part of broader confidence-building efforts, even if more formal and intrusive verification initiatives were not adopted.

These forms of "cooperative transparency" could be augmented by information gathered unilaterally by individual states, which is current U.S. arms control and nonproliferation practice. The available methods include "National Technical Means" (NTM) such as satellite imagery collected over a range of wavelengths, imagery from reconnaissance aircraft, data from chemical and radiological detectors on aircraft overflying a country or patrolling just outside its borders, and intercepted electronic communications. They also include information gathered by human sources—clandestine operatives—and information obtained from defectors or "whistle blowers."

DECLARATIONS OF NUCLEAR WEAPON STOCKS

The logical first step toward increased transparency would be for nuclear weapon states to exchange information on their inventories of nuclear weapons. Alternatively, a declaration or data exchange could be part of a formal agreement. Most arms control agreements have included provisions for initial and subsequent declarations of treaty-limited items; examples include START I, the Treaty on the Elimination of Intermediate-Range Missiles (INF Treaty), the Treaty on Conventional Armed Forces in Europe, and the Chemical Weapons Convention (CWC). In each of these cases, the initial declaration defined a baseline inventory from which the agreed reductions proceeded. A formal agreement has the advantage of precision since it could define the items covered and specify exactly what information is to be exchanged; for example, an agreement might define what constitutes a "nuclear weapon" (see Box 2-1) and specify when a weapon would be considered dismantled or eliminated.

Declarations could also be made unilaterally and informally, with or without the expectation of reciprocation by other nuclear weapon states. The main advantage of voluntary declarations is that they can be accomplished quickly, without lengthy and detailed negotiations. The United States could lead by example, declaring its inventories of weapons and inviting other states to do the same. Given the size of the U.S. nuclear arsenal, making a unilateral declaration would not incur a security risk, but the United States would lose bargaining leverage in negotiating greater transparency if Russia did not reciprocate. The major disadvantage of this approach is that there would be no agreed definitions of exactly what should be declared and therefore no basis for transparency measures to confirm the accuracy of the information provided. This proved to be a problem with the informal Presidential Nuclear Initiatives on nonstrategic nuclear weapons announced by the United States and Russia in 1991-92, where lack of a formal agreement, detailed exchanges of information, or transparency measures at one point led some to charge that Russia was redeploying weapons in violation of its previous pledge, despite Russian denials.[3]

Proposals for U.S.-Russian Declarations

Proposals for weapon declarations and related transparency measures emerged in the wake of the breakup of the Soviet Union.

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[3] See Rose Gottemoeller, "Offense, Defense, and Unilateralism in Strategic Arms Control," *Arms Control Today* 31 (September 2001), pp. 10-15. Bill Gertz, "Russia Transfers Nuclear Arms to Baltics," *The Washington Times*, January 3, 2001, p. A1.

In 1992 concern about the safety and security of nuclear weapons and NEM in the former Soviet Union led Senator Joseph Biden to introduce the following amendment to the resolution of ratification for the START I Treaty:

> *Nuclear Stockpile Weapons Arrangement.* Inasmuch as the prospect of a loss of control of nuclear weapons or fissile material in the former Soviet Union could pose a serious threat to the United States and to international peace and security, in connection with any further agreement reducing strategic offensive arms, the President shall seek an appropriate arrangement, including the use of reciprocal inspections, data exchanges, and other cooperative measures, to monitor (A) the numbers of nuclear stockpile weapons on the territory of the parties to this Treaty; and (B) the location and inventory of facilities on the territories of the parties to this treaty capable of producing or processing significant quantities of fissile materials.[4]

The amendment was interpreted to apply to a future START III treaty, since the START II negotiations were already moving to a conclusion at that time.

In 1994 the United States began trying to gain Russian agreement to greater transparency; since most of these efforts included both weapons and NEM, they are described together here. The United States had several motives for these initiatives: to fulfill the requirements of the Biden Amendment in anticipation of a future START III treaty; to facilitate U.S. assistance to Russia under the Cooperative Threat Reduction (CTR) program; and to bolster international support for the indefinite extension of the Nuclear Non-Proliferation Treaty (NPT). As described elsewhere in this study (see Chapter 3), part of this effort included a significant amount of joint work between the U.S. and Russian nuclear weapons laboratories to explore transparency and monitoring measures that could make this increased openness possible while still protecting sensitive information about weapon designs.

At their summit in September 1994 Presidents Clinton and Yeltsin agreed to “exchange detailed information…on aggregate stockpiles of nuclear warheads, on stocks of fissile materials and on their safety and security. The sides will develop a process for

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[4] *The START Treaty*, Executive Report (Washington, DC: U.S. Government Printing Office, September 18, 1992), pp. 102-153.

exchanging this information on a regular basis."[5] Their May 1995 summit statement reaffirmed that the two governments would negotiate agreements on stockpile data exchanges, and called for a third agreement on "other cooperative measures, as necessary to enhance confidence in the reciprocal declarations on fissile material stockpiles." The two presidents also agreed to "examine and seek to define" possibilities for "intergovernmental arrangements to extend cooperation to further phases of the process of eliminating nuclear weapons."[6]

The United States formally presented the draft text of an agreement to Russia in June 1995. The proposal included a call for a confidential exchange of data on current total inventories of weapons and NEM, as well as on the total number of nuclear weapons dismantled each year since 1980 and the type and amount of NEM produced each year since 1970. The Russians declined to discuss the draft, however. According to James Goodby, U.S. chair of the joint working group that had been exploring the arrangements, some Russian members of the group "gave the impression that the scope of the data exchange went well beyond what they were prepared to consider."[7]

The United States nonetheless continued to seek agreement on stockpile declarations. At their March 1997 summit in Helsinki, Presidents Clinton and Yeltsin agreed that a START III agreement, to be negotiated following ratification of START II, should include "measures relating to the transparency of strategic warhead inventories and destruction of strategic nuclear warheads" and that transparency measures related to nonstrategic nuclear weapons and to nuclear materials would also be explored.[8] When the United States presented a draft protocol dealing with transparency and monitoring for weapons in early 2000 for consideration in connec-

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[5] Joint Statement on Strategic Stability and Nuclear Security by the Presidents of the United States of America and the Russian Federation (Washington, DC: The White House, Office of the Press Secretary, September 28, 1994), p. 3.

[6] Joint Statement on the Transparency and Irreversibility of the Process of Reducing Nuclear Weapons (Washington, DC: The White House, Office of the Press Secretary, May 9-10, 1995).

[7] James Goodby, "Transparency and Irreversibility in Nuclear Warhead Disarmament," in Harold A. Feiveson, ed. *The Nuclear Turning Point: A Blueprint for Deep Cuts and De-Alerting of Nuclear Weapons* (Washington, DC: Brookings Institution Press, 1999), p. 186.

[8] Joint Statement on Parameters on Future Reductions in Nuclear Forces (Washington, DC: The White House, Office of the Press Secretary, March 21, 1997).

tion with START III, however, the Russians were not interested in pursuing the idea.[9] In the end, START II never entered into force, and START III negotiations were never initiated. The obstacles to more far-reaching transparency—in the form of deep-rooted mutual suspicion about motivations, desire to protect sensitive information, and bureaucratic and legal impediments on both sides—are formidable, not least because some of them reflect genuine dilemmas about the balance of risk and benefit.[10]

Although no formal agreements on stockpile declarations have been achieved, some data have been released on a voluntary basis. No nuclear weapon state has revealed the precise number of nuclear weapons in its current stockpile; however, the United States, the United Kingdom, and France have released some information. The United States released an official accounting of the total number of nuclear weapons in its stockpile each year from 1945 to 1961; the total yield of the stockpile and the number of weapons retired or dismantled each year from 1945 to 1994; and, for fully retired weapon types, the total number assembled each year.[11] Although it did not provide such historical details, the United Kingdom has stated that in the future it would maintain fewer than 200 operationally available weapons of a single type.[12] In the mid-1990s France announced that it would eliminate its land-based nuclear forces, reduce the number of strategic submarines it would deploy, and dismantle the facilities used to produce NEM for nuclear weapons.[13]

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[9] Rose Gottemoeller, "Parsing the Nuclear Posture Review," A ACA Panel Discussion With Daryl G. Kimball, Janne E. Nolan, Rose Gottemoeller, and Morton H. Halperin, *Arms Control Today* 32 (March 2002), pp. 15-21. Available as of January 2005, at: http://www.armscontrol.org/act/2002_03/panelmarch02.asp

[10] For a discussion of these issues from both U.S. and Russian perspectives, see National Research Council, *Overcoming Impediments to U.S.-Russian Cooperation on Nuclear Nonproliferation: Report of a Joint Workshop* (Washington, DC: The National Academies Press, 2004).

[11] Declassification of Certain Characteristics of the United States Nuclear Weapon Stockpile. Fact Sheet (Washington, DC: U.S. Department of Energy, June 27, 1994). Available as of January 2005, at: http://www.osti.gov/html/osti/opennet/document/press/pc26.html.

[12] British Ministry of Defence, "Strategic Defence Review: Deterrence and Disarmament" (London: Ministry of Defense, July 1998). Available as of January 2005, at: http://www.mod.uk/issues/sdr/deterrence.htm.

[13] Robert S. Norris, William M. Arkin, Hans M. Kristensen, and Joshua Handler, "French Nuclear Forces," *Bulletin of the Atomic Scientists* 57 (July/August 2001), pp. 70-71.

Levels of Detail in Stockpile Declarations

Information on nuclear weapon stockpiles could be exchanged at various levels of detail, from highly aggregated to data on individual weapons. Table 2-1 illustrates this progression using four levels of detail: total number of weapons; total inventories by weapon type and status; inventories by facility; and a complete itemized inventory.

TABLE 2-1 Illustrative Levels of Detail for Declarations of Weapon Inventories

Level	Type of Information
1	Current total number of nuclear weapons of all types. Each year since first test: total number assembled, disassembled, and in the stockpile. For each of next five years: planned number assembled, disassembled, stockpiled.
2	Current total number of each weapon type, by status (e.g., operationally deployed, active reserve, inactive reserve, retired/awaiting dismantling). Delivery systems associated with each weapon type. Each year since first test: total number of each weapon type assembled, disassembled, and in the stockpile. For each of next five years: planned number of each type assembled, disassembled, and in the stockpile.
3	Name and location of all facilities at which nuclear weapons are currently deployed, stored, assembled, maintained, remanufactured, dismantled, or other otherwise handled. Facility descriptions and site maps indicating each launcher, storage bunker, building, or other site in which nuclear weapons are or may be located. Number of each weapon type at each facility. Name and location of facilities that previously contained weapons.
4	For each weapon: serial number, weapon type, status, and current location.

Total Inventories

The simplest declaration would give the total number of nuclear weapons currently possessed by each state. Even at this general level there are technical issues to resolve, such as whether unassembled or partly assembled weapons, test or mock devices, and explosive devices not intended for military use would count as "weapons" for the purposes of the declaration.

The total worldwide stockpile of nuclear weapons is probably around 30,000, of which the arsenals of the United States and Russia constitute 95 percent. China, France, and the United Kingdom collectively account for 3 to 4 percent of the worldwide total, while Israel, India, and Pakistan together account for less than 1 percent. Although actual weapon inventories remain state secrets in each of these countries, we do not find a persuasive security rationale for keeping secret the total number of weapons held by each of the five *de jure* nuclear weapon states (i.e., the five states recognized as such by the NPT). The potential confidence-building value of such declarations is underscored by the substantial uncertainties in some official U.S. estimates; for example, for Russia this may be as large as "plus or minus 5,000" weapons.[14] Most of this is due to large uncertainties about Russia's stock of nonstrategic weapons, which may account for more than half of the Russian stockpile.

It could also be very useful to declare historical weapon inventories to help build confidence in the accuracy and completeness of declarations of current inventories. States willing to share current data could also be willing to share comparable historical data. Beginning with the year of their first nuclear test, states could give the total number of weapons assembled and disassembled each year and the total number in the stockpile at the end of the year. States also could share information on their future plans for the weapon stockpile, giving, for example, the projected number of weapons to be assembled and dismantled each year for the next five years.

Inventories by Type and Status

The next level of detail would disaggregate total inventories by weapon type and/or associated delivery vehicle. The inventory could be further disaggregated by status, to differentiate between "active" weapons (those ready for immediate military use) and

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[14] See, for example, Lawrence Gershwin, National Intelligence Officer for Strategic Programs, *DOD Appropriations for FY93*, testimony before the House Committee on Appropriations, Part 5, (May 6, 1992), p. 499; and Gen. Eugene Habiger, U.S. Air Force, Former Commander U.S. Strategic Command, The Moscow Treaty. "The Treaty between the United States of America and the Russian Federation on Strategic Offensive Reductions," Testimony before the Senate Foreign Relations Committee, (July 23, 2002).

"inactive" weapons (those without tritium and other limited-life components installed). Active weapons could be divided into operationally deployed weapons (i.e., mated with a ballistic missile or ready for immediate aircraft delivery) and other weapons that could be deployed relatively quickly (i.e., spares and reserves). The inactive inventory might also be further divided into reserve weapons and weapons that have been permanently retired and are awaiting dismantling.

As with total inventories, it could also be useful to release comparable historical data and share future plans. For each weapon type (including types not in the current stockpile), for example, states could declare the number of weapons assembled and disassembled in each year since the first nuclear test and the total number of each type in the stockpile.

Today, inventories by type and status are state secrets. In the case of Russia and the United States, which have exchanged detailed information on deployed strategic forces, such secrecy only serves to protect information on the number of nonstrategic and reserve strategic weapons. We judge that the potential security benefits of exchanging these data outweigh the benefits of continued secrecy.

Facility Inventories

The next level of detail would disaggregate weapon inventories by facility, which would be necessary before states could consider the possibility of inspections or other measures to confirm the accuracy of declarations. At this level, states would declare the name and location of all facilities at which nuclear weapons exist, preferably by type and status. Facility descriptions and site diagrams also could be exchanged, indicating the location of all storage bunkers or other areas where nuclear weapons might be present. The United States and Russia have exchanged information at this level of detail for nuclear delivery systems under the INF and START treaties, in order to facilitate verification of agreed reductions and limits.

Relevant facilities would include intercontinental ballistic missile (ICBM), submarine, and air bases; nuclear weapon storage facilities at other military bases; and facilities at which weapons are assembled, disassembled, or maintained. A declaration could be prepared for each such facility. For example, states could declare the total number of weapons of each type mounted on ICBMs or stored as spares at each ICBM base, the number stored or deployed on submarines based at each port, the number of active and inactive weapons of each type in each storage facility, and so on. (For very small inventories, weapons in transit would need to be declared and controlled as well, since transport systems could in that case conceal a significant fraction of the stockpile.)

Much of this information has already been exchanged by the United States and Russia, as part of the START Treaty. Going beyond START, they could share information on facilities where nonstrategic weapons are deployed, and the location and inventory of weapon storage, maintenance, and assembly-disassembly facilities. It might be argued that providing such information would allow these facilities to be targeted, but it is reasonable to assume that Russia and the United States have already identified and characterized each other's nuclear weapon facilities, and the military significance of these facilities is much smaller than that of deployed forces in any case.

Serious security concerns would arise if declarations significantly increased the vulnerability of a state's nuclear forces to attack; for example, declarations that included the location of every nuclear weapon might prove destabilizing if potential adversaries became more confident in their ability to destroy opposing forces (and therefore be tempted to launch a preemptive attack during a crisis) or more afraid of preemptive attack (and therefore more likely to launch nuclear forces before they could be destroyed). This should not be a concern, at least for the United States and Russia, for several reasons. First, the United States, Russia, France, and the United Kingdom maintain submarines at sea (and, in the case of Russia, also mobile ICBMs) that cannot be targeted or confidently destroyed in a preemptive attack. Second, the United States and Russia also deploy silo-based ICBMs that could, at least in principle, be launched on warning of an attack, further inhibiting each other from contemplating a preemptive attack. Third, as discussed below (see "Secure Declarations"), the use of cryptographic tools could allow parties to maintain control over access to the information contained in the declarations, so that the location of every nuclear weapon need not be revealed in advance.

Itemized Inventory

The most detailed declaration would be an itemized inventory. This could take the form of a table with a row for each weapon and columns for the weapon's serial number, type, date of assembly, status, and location. The table could be extended to include weapons and other nuclear-explosive devices that had been dismantled or destroyed in explosive tests.

Today such itemized inventories would be considered highly sensitive, and the exchange of such information is unlikely to receive serious attention in the near future. That said, sharing and confirming weapon inventories at this level of detail ultimately would be necessary—though not sufficient—to achieve very deep cuts in U.S.-Russian nuclear arsenals. One of the most difficult technical issues associated with very deep cuts would be gaining high confidence in a state's baseline inventory of nuclear weapons. If a complete, correct baseline inventory could be confidently established, transparency and monitoring to demonstrate that all weapons contained in the inventory (or all but an agreed number) have been dismantled would provide confidence in the accuracy of deep cuts. The Chemical Weapons Convention, which prohibits chemical weapons, requires parties that possess such weapons to declare the precise location and give a detailed inventory of each facility.

Secure Declarations

In the approach described above, access to stockpile data is controlled by limiting the types of information exchanged. As trust and cooperation grew between parties, the level of detail and types of information exchanged could be expanded incrementally, from highly aggregated to itemized declarations. One problem with this incremental approach is that high confidence in the accuracy of declarations would be deferred until the final stages of this process, because simple and aggregated declarations are much easier to falsify than detailed and itemized declarations. In addition, states would be less likely to have confidence in future declarations of smaller nuclear arsenals if there had not been a steady flow of detailed information over the intervening years about the assembly, dismantling, and inventories of each type of weapon, beginning when arsenals were much larger. Early declarations, involving weapons not yet subject to agreed reductions or elimination, would force states to decide, at the outset of the process, whether to make a completely truthful declaration, thereby constraining the potential for cheating or making cheating more detectable at a later date. In some cases, however, disclosure of stockpile data, if made public, could fuel or exacerbate interstate rivalries and put pressure on governments to increase the number of nuclear weapons.

It could take many years to build mutual trust to the point where parties would be willing to exchange complete and detailed stockpile information. In the intervening time, the opportunity for exchanging and confirming information about the assembly or dismantling of weapons would be lost. This could present a "chicken-and-egg" dilemma, in which deeper trust and cooperation depended upon the prior exchanges of information, but these prior exchanges required deep levels of trust and cooperation.

This dilemma could be resolved by using modern information technology. Cryptographic tools are readily available (see Box 2-2) that would allow states to exchange detailed stockpile data while maintaining complete control over access to its contents. In this way, states could begin at an early date to exchange detailed and complete declarations on a regular basis, granting other parties access to selected portions of the data, on a sampling basis or on an agreed schedule. By confirming the accuracy of small random samples of the data, parties would over time develop high confidence that declarations were accurate, even if they never had complete access to the entire declaration. The declarations would, in effect, be placed in "escrow" until such time as both parties agreed to exchange part or all of the information contained therein. Complete access to the declarations might be granted years later and examined for internal consistency and for consistency with information gathered during inspections and with national technical means. This is conceptually similar to a sealed bid that is deposited by a deadline and opened by the auctioneer at a later time, except in this case the envelope can be opened only with the cooperation of the bidder.

One technique for preparing and exchanging secure declarations is encryption. Standard encryption algorithms, such as the Advanced Encryption Standard,[15] are routinely used by U.S. government agencies to transmit secret information. To see how encrypted declarations might work, assume that Russia and United States agreed on the data that ultimately should be exchanged and a format for these data. The data file might contain a line or record for each weapon, for example, with each record containing the several data fields: serial number, type, date of assembly, its location and status on a certain date, and so forth. Each record would

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[15] National Institute of Standards and Technology, "Specification for the Advanced Encryption Standard," Federal Information Processing Standards Publication 197 (November 26, 2001). Available as of January 2005, at: http://csrc.nist.gov/publications/fips/fips197/fips-197.pdf.

also have a large “nonce” field, containing characters chosen at random, so that identical records would not have identical cipher texts. If each record is encrypted with a different cryptographic key, the party making the declaration could control access to each record individually. According to agreed rules, other parties could request decryption of selected records or all the records corresponding to a selected facility. By confirming the accuracy of a small random sample of records (e.g., through site visits), parties could gain confidence in the accuracy of the entire declaration even while most of it remained encrypted. The total number of weapons would be revealed by the total number of records; if desired, separate files could be exchanged for each facility or each category or type of weapon, thereby revealing the total number of weapons of each type or at each facility. If at an early stage parties did not want to reveal the total number of weapons, a large number of nonce records could be included in the declaration.

Another technique for exchanging secure declarations makes use of message digests. A digest is a unique digital fingerprint of a message. Government-approved techniques for producing and using digests (e.g., the “secure hash” algorithm or SHA-1) are routinely and widely used to authenticate electronic signatures and financial transactions.[16] No keys are involved. One cannot determine the content of a message from its digest; there simply is not enough information in the digest to allow construction of the matching record, and the nonce field prevents the guessing of a record based on its digest. The digest produced by SHA-1 is secure because it is computationally infeasible to discover a message that corresponds to a particular digest. It is similarly infeasible for the party providing the digest to cheat by producing a second message that produces the same digest.

To see how message digests might be used, assume that a detailed declaration is prepared in an agreed format as described above, with a record for each weapon, and that parties have agreed on an algorithm for producing message digests. The declaring party could produce and provide the inspecting party with a separate digest for each record in the declaration. According to agreed rules, another party could select a particular digest and request

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[16] Representative government-approved hashing algorithms may be found in National Institute of Standards and Technology, “Secure Hash Standard,” Federal Information Processing Standards Publication 180-2 (August 1, 2002). Available as of January 2005, at: http://csrc.nist.gov/publications/fips/fips180-2/fips180-2.pdf. For example, the SHA-1 algorithm provides for messages of up to 2^{64} bits (more information than is contained in the largest library) to be digested in just 160 bits (less information than is contained in this sentence).

revelation of the corresponding record, process this record with the agreed algorithm and confirm that the digest produced is identical to that provided previously, and then verify the accuracy of information contained in the record through site visits, as discussed below. In this way, parties could gain high confidence in the accuracy of the entire declaration, even while most of it was represented only by the corresponding message digests.

Frequency and Confidentiality of Declarations

Informal declarations might be sporadic or a one-time affair, but a formal agreement could be expected to include provisions for the regular exchange or updating of declarations at agreed intervals. The INF and START I treaties, for example, established and successfully implemented a six-month interval for the exchange of data on the number of deployed delivery vehicles and launchers. Regular data exchanges should not impose a significant additional burden on states, as they presumably maintain a complete, detailed, and up-to-date database of weapon inventories for their own use.

In the event of very deep reductions in the number of nuclear weapons, there could be a desire for more frequent exchanges of information. In the long term, it might be possible to update declarations almost continuously; for example, one could construct a system that would continuously monitor weapons in a storage area and report this information on a real-time basis to other parties. One could also write a computer program that would automatically produce, from a state's official nuclear weapon database, an encrypted declaration or a digest for transmission to other parties every time the official database is changed.

Finally, there is the issue of whether declarations should be made public or kept confidential between the parties. There is precedent for both approaches: the data on nuclear forces exchanged by Russia and the United States under the INF and START treaties were made public; declarations made by parties to the CWC and the NPT are confidential. The 1995 U.S. proposal on weapon and NEM declarations called for a confidential exchange of data between Russia and the United States on weapon inventories.

Although it may seem that a state should be willing to make public any stockpile data that it is prepared to share with potential adversaries, there is an overriding shared interest in preventing the release of information that could be useful to states or groups interested in acquiring nuclear weapons. There may be information, such as the precise locations where nuclear weapons are stored or the measures that are used to protect or account for them, that nuclear weapon states would be willing to share with each other but not more generally, for fear that its release could aid someone wishing to develop or to steal nuclear weapons. As mentioned above, states may also fear that releasing information on the locations of nuclear weapons could trigger public opposition and protests or even terrorist attacks. The United States and its NATO allies, for example, might be reluctant to announce the locations of the small number of nuclear weapons for use on tactical aircraft based in Europe (even though nongovernmental organizations claim to know and have published these locations).[17]

We believe that confidential declarations can achieve most of the security benefits of increased transparency. If, however, declarations are intended to reassure publics and non-nuclear weapon state governments that nuclear weapon states are reducing their inventories of nuclear weapons, declarations should be made as openly available as possible.

CONFIRMING WEAPON DECLARATIONS

Declarations of weapon stocks could have value as a confidence-building measure even without measures to confirm their accuracy. If, however, declarations were intended to serve as the basis for agreed reductions in nuclear weapon stockpiles, we assume the parties to such an agreement would want verification measures, such as site visits and mutual inspections, to confirm their accuracy. The INF, START, and CWC treaties, for example, all provide for baseline or initial inspections to verify the accuracy of declarations as a prelude to agreed reductions or the elimination of weapons.

Site visits and inspections could have other benefits. By opening up formerly secret facilities, such as nuclear weapon storage sites, other parties can confirm that weapons are stored safely and securely against theft or diversion. This could make it possible for states to learn from each other, facilitating peer review and cooperation in improving the safety and security of weapon handling

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[17] See for example, William M. Arkin, Robert S. Norris, and Joshua Handler, “Taking Stock: Worldwide Nuclear Deployments 1998” (Washington, DC: Natural Resources Defense Council, 1998). Available as of January 2005, at: http://www.nrdc.org/nuclear/tkstock/tssum.asp.

and storage, and setting standards for the extension of agreements on nuclear weapon limits to other states.

This chapter deals only with confirming the accuracy of weapon declarations at declared facilities. Chapter 4 considers the important and difficult issue of confirming the completeness of a declaration—that is, how confident one can be that additional weapons (and NEM) do not exist at other, undeclared facilities.

Operationally Deployed Weapons on Missiles

Russia and the United States have already devised procedures to confirm the number of operationally deployed weapons on missiles. START I provides for on-site inspections at ICBM and submarine-launched ballistic missile (SLBM) bases to confirm declarations of launchers and the missile type associated with each launcher. Moreover, the number of ICBM silos and SLBM launch tubes is easily confirmed with photoreconnaissance satellites, and verification of mobile ICBMs is facilitated by START I requirements to openly display upon request all mobile launchers at selected bases and to allow continuous on-site monitoring of assembly facilities for mobile ICBMs. These measures provide high confidence that declarations of deployed ICBMs and SLBMs are accurate and complete.

Under START I, Russia and the United States also specify the number of weapons permitted on each missile type. Each missile of a given type is counted as having the permitted number of weapons. This usually corresponds to the maximum number of weapons with which the missile has been tested or deployed, but START I allows each side to "download" missiles subject to certain limitations; for example, the United States is allowed to reduce the number of weapons permitted on its Minuteman III ICBMs from three to one, and Russia is allowed to reduce the number permitted on its SS-N-18 SLBMs from seven to three. Downloading presumably will be the principal method both sides will employ to comply with the limits established by the Moscow Treaty (e.g., the number of weapons on the Trident II SLBM could be reduced from eight to five).

To help confirm that missiles are armed with no more than the permitted number of weapons, START I provides for a limited number of reentry vehicle inspections of deployed ballistic missiles (silo-based ICBMs, mobile ICBMs in garrison, and SLBMs on submarines in port). Parties may request up to 10 such inspections per year, with no more than 2 at any given base. The inspecting party selects a particular base and then a particular launcher within the base. The inspected party must demonstrate that the number of reentry vehicles on the selected missile does not exceed the number permitted. In practice, this has been done by removing the missile's shroud and fitting covers over each reentry vehicle, or fitting over the front section of the missile a hard cover that contains indentations to accommodate each reentry vehicle. Although inspectors cannot see the reentry vehicles, they can verify that the number or shape of the covers could not accommodate more than the permitted number of weapons for that type of missile. In case of ambiguities, START I allows the use of radiation measurements to determine that an object is not a weapon.

If parties deploy fewer than the permitted number of weapons on some missiles, additional procedures may be necessary to confirm a declaration of the actual number of deployed weapons; for example, the inspecting party could determine the number of weapons by moving a radiation detector around the perimeter of the missile. Procedures for using a neutron detector to distinguish between the single-weapon SS-25 missile and the three-weapon SS-20 missile were worked out for the INF Treaty.

Sampling

The START I reentry vehicle inspections illustrate how the design of an inspection system can enable the use of sampling, which can greatly reduce the cost and intrusiveness of verification. With such a system, inspecting a small sample of missiles can produce high confidence in the accuracy of the entire declaration. As a simple example, assume a country has 500 deployed missiles and that four weapons are declared for each missile, for a total of 2,000 declared weapons. Further assume that the country cheats by arming 100 of these missiles with eight weapons, for an actual total of 2,400 weapons (20 percent more than the number declared). If 10 randomly selected missiles were inspected each year, there would be a 90 percent chance of detecting this violation during the first year, and a 99 percent chance after two years.[18] Smaller violations

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[18] If missiles are selected at random, all missiles are equally likely to be inspected and the probability of selecting a missile armed with more than the permitted number of weapons is (100/500) = 0.2. The probability that ten inspections would not include one such missile is about $(0.8)^{10} = 0.107$, so there is a 89.3 percent chance of uncovering a violation (assuming that extra weapons will be detected if they exist on inspected missiles). In general, P is given approximately by the formula $P = 1 - (1-F)^n$, where F is the fraction in violation, n is the number sampled, and P is the probability that the sample contains at least one item in violation. This approximation is valid if the number in-

would have a lower but substantial probability of detection; in the above example, after one year there would be a 65 percent chance of detecting a 10 percent increase in the number of weapons, and an 88 percent chance after two years.

Sampling is likely to produce even greater confidence in the accuracy of declarations than indicated by these calculations if inspectors can target facilities where violations are thought to be more likely. If the inspecting party has intelligence information pointing to suspicious activity at particular sites, these sites could be selected for inspection. Similarly, a larger share of the inspection effort could be allocated to those missile types that can be armed with more (perhaps many more) than the declared number of weapons; for example, under reasonable assumptions about weapon loadings and the numbers of deployed missiles, inspection of just four Minuteman III missiles, three Trident II or SS-N-18 missiles, or two SS-19 missiles would give a 90 percent chance of a 20 percent increase detecting in the number of weapons above

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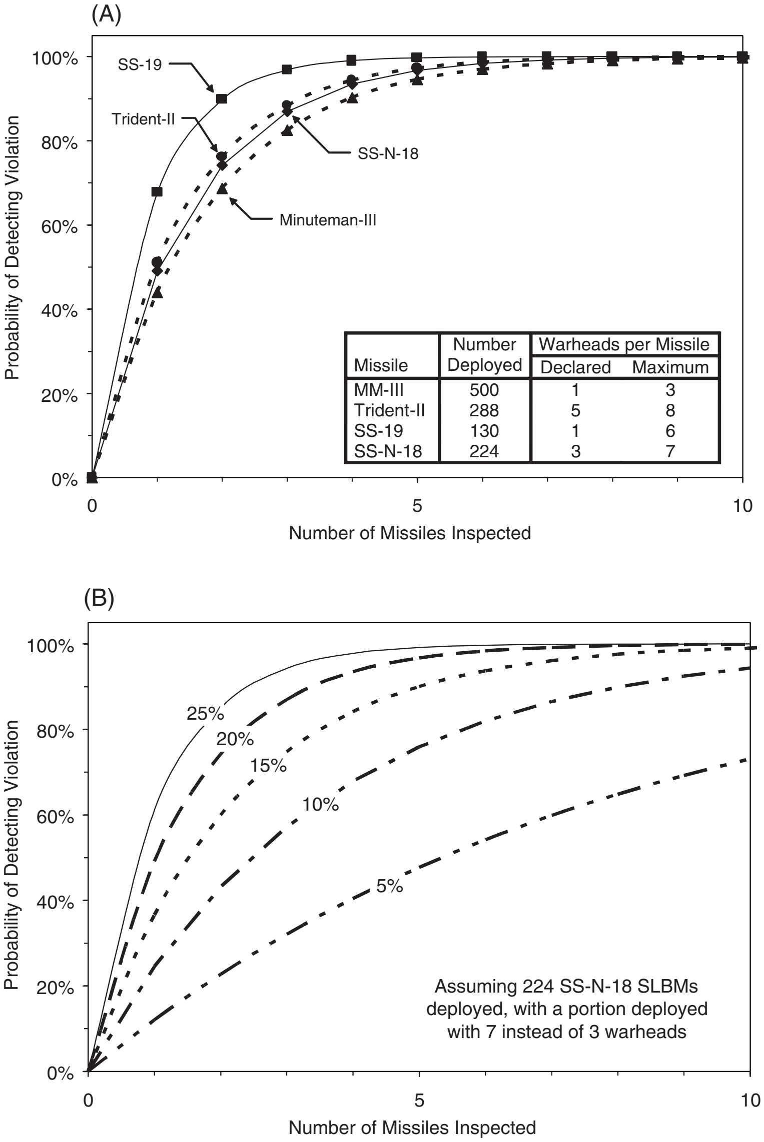
spected is small compared to the total number of missiles. The exact formula is $P = 1 - [(N-M)!(N-n)!]/[(N-M-n)!N!]$, where N is the total number of missiles and $M = FN$ is the number of missiles in violation; in this example, $P = 1 - [(400!490!)/(390!500!)] = 0.895 \approx 90$ percent.

Some would interpret this calculation to mean that ten inspections would give 90 percent confidence of compliance, or 90 percent confidence that the actual number of deployed weapons on missiles is less than 2,400. A proper calculation of the confidence in compliance produced by inspections would, however, take into account prior beliefs about the likelihood of cheating. If, for example, the inspecting party believed, before the inspections began, that there was a 10 percent chance of cheating as described above (i.e., a prior probability of compliance of 0.9), then ten inspections that uncovered no evidence of cheating would result in a posterior probability of compliance of 99 percent. The general formula is $P_c' = P_c/[1-P(1-P_c)]$, where P_c and P_c' are the prior and posterior probabilities of compliance and P is the probability that the inspections would uncover evidence of cheating if it existed; in the above example, $Pc' = 0.9/[1-(0.895)(0.1)] = 0.9885$. The posterior probability of compliance (P_c') is greater than the probability that inspections would detect cheating (P) if the prior probability of compliance (P_c) is greater than 0.5.



Missile	Number Deployed	Warheads per Missile	
		Declared	Maximum
MM-III	500	1	3
Trident-II	288	5	8
SS-19	130	1	6
SS-N-18	224	3	7

Assuming 224 SS-N-18 SLBMs deployed, with a portion deployed with 7 instead of 3 warheads

FIGURE 2-2 Illustrative examples of the probability of detection. This figure illustrates examples of the probability of selecting at least one missile armed with more than the declared number of weapons, as a function of the total number of missiles selected for inspection. The top figure assumes that the inspected party has deployed a total of 440 extra weapons (beyond those allowed or declared) on each of four U.S. and Russian missile systems, by arming a portion of the deployed force with the maximum number of weapons the missile can carry. The bottom figure illustrates how the probability of detection varies with the size of the violation, assuming that a portion of the Russian SS-N-18 SLBM is armed with 110, 220, 330, 440, and 550 extra weapons (5, 10, 15, 20, and 25 percent more than the total number of operationally deployed weapons allowed by the Treaty of Moscow).

the limit of 2,200 operationally deployed weapons set by the Treaty of Moscow.[19] Doubling the number of inspections would increase the probability of detection to 99 percent. Figure 2-2 illustrates the increase in the probability of detecting a violation with the total number of missiles selected for inspection.

Stored Nuclear Weapons

Today, all nuclear weapons are either deployed or in some type of storage.[20] Deployed strategic and nonstrategic weapons are mounted on missiles or are stored at air bases for nuclear-capable aircraft. Spare weapons may be stored at ICBM or SLBM bases and reserve strategic and nonstrategic weapons at central storage facilities. Weapons that have been retired or otherwise scheduled for elimination can be found at disassembly facilities.

Nuclear weapons are stored in special structures that are variously referred to as bunkers, magazines, igloos, or vaults. Individual bunkers, such as those pictured in Figure 2-3, may contain a few to two dozen weapons. Central storage facilities may contain

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[19] The Treaty of Moscow permits a maximum of 2,200 operationally deployed weapons. The deployment of an additional 440 weapons would represent a 20 percent violation. This could be achieved by uploading 220 of 500 Minuteman III missiles from one to three weapons, 147 of 288 Trident II missiles from five to eight weapons, 88 of 130 SS-19 missiles from one to six weapons, or 110 of 224 SS-N-18 missiles from three to seven weapons. Confidence in compliance would be considerably higher than 90 percent if the prior probability of cheating were low.

[20] Exceptions might include strategic defensive weapons on antiballistic missile interceptors; weapons in transit between facilities; weapons undergoing maintenance, remanufacture, or dismantling; and, perhaps in the case of China, certain nonstrategic weapons. Transparency measures could be developed to cover these exceptions, if desired; for example, confirming nuclear weapons on anti-missile interceptors could be accomplished in much the same way as described above for ballistic missiles.

several dozen such bunkers or a single structure divided into many vaults or bays. Storage facilities are blast resistant and usually earth bermed or located underground in order to limit the damage that would be caused by an accidental detonation of the high explosive in the weapons, and to protect the weapons from attack.

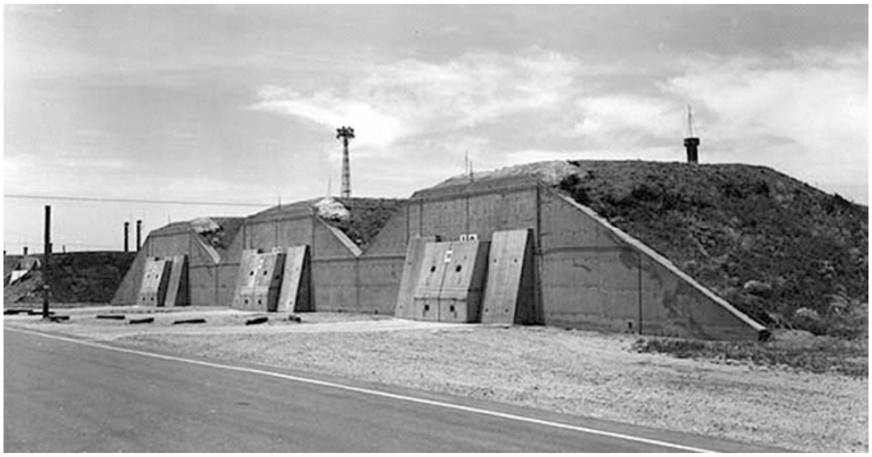

FIGURE 2-3 Storage bunkers at the Pantex weapon assembly plant in Texas.

Thousands of nuclear weapons are stored in the United States at numerous Air Force and Navy bases and the Pantex weapon assembly plant, and a small number of weapons are stored overseas. The corresponding numbers for Russia are less well known. The reduction and consolidation in U.S. and Russian nuclear forces over the last decade means that many facilities at which nuclear weapons were stored in the past are now empty or have been converted to other uses.

In order to confirm declarations of stored weapons, the declaration could include the location of each facility, site maps indicating the weapon storage area and the location of each bunker, and the number of nuclear weapons in each bunker or vault. As with reentry vehicle inspections, parties might be granted an annual quota of weapon storage inspections; for example, 10 per year, with no more than 2 at the same facility. Again, high confidence in the accuracy of the declaration could be achieved based on a small number of inspections. Suppose, for example, that a party had declared a total of 500 storage bunkers with 10 weapons in each bunker

(5,000 declared weapons) but had cheated by doubling the number of weapons in 100 of the bunkers (6,000 weapons, or 20 percent more than the number declared). If 10 randomly-selected bunkers are inspected, there would be a 90 percent chance that at least 1 of the 10 would contain extra weapons.[21]

Depending on the system, an inspection could begin with the selection of a particular facility from the list of declared storage facilities. The weapon storage area at this facility would immediately stand down; movement of weapons, entry or exit of weapon transport vehicles, and the opening of bunker doors would be suspended until the inspection was completed. Inspectors could then select a particular storage bunker for inspection and confirm that the number of weapons in the bunker matched the number in the declaration. If secure declarations were part of the monitoring system, then the records for that bunker could be provided and compared with the digests that had been provided earlier. Alternatively, the inspecting party could randomly select some number of digests for the facility, request the records corresponding to these digests, and then ask to see the matching weapons.[22]

As with any procedure involving nuclear weapons, strict health and safety standards would apply to storage inspections. Inasmuch as personnel enter weapon storage facilities from time to time to take inventory and perform routine maintenance, it seems reasonable to expect that procedures could be developed that would give inspectors access to such facilities without significant risk to themselves or others.

Inspection of the chosen bunker could be accomplished in much the same manner as a regular inventory check: a visual inspection that matched each weapon in the bunker with a weapon in the declaration. It is likely that most weapons are in containers and that a visual inspection would not reveal any sensitive information, but if this were a concern the inspected party could be permitted to cover or drape weapons prior to inspectors entering the bunker.

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[21] The calculation is identical to that in Footnote 18, and assumes all bunkers are equally likely to be selected for inspection (i.e., that the likelihood of selecting a facility for inspection is proportional to the number of bunkers at the facility). Of course, inspections may target bunkers that are declared to be empty or to contain relatively few weapons, since the potential for cheating is larger at these bunkers. If no violations are detected, confidence in compliance would be considerably higher than 90 percent if the prior probability of cheating was low.

[22] If weapons were moved after the most recent declaration (e.g., for maintenance or disassembly), the inspected party would have to give prompt notification of their new location and status.

Once inside the bunker, inspectors would have two basic tasks: identifying the nuclear weapons and matching them to the declaration, and determining that other objects are not nuclear weapons. Regarding the first task, it might be sufficient for the inspected party simply to point out each weapon, because the inspected party would have little incentive to claim that an object is a weapon when it is not. (An exception is when a weapon is retired and slated for dismantling; in this case, the inspecting party would want to make sure that the object about to be dismantled was a genuine weapon.) If parties had exchanged itemized inventories, the inspecting party could check that the serial numbers on the weapons or weapon containers matched the serial numbers given in the declaration. Tags could be used for this purpose instead of serial numbers (see Box 2-3). Discovery of a weapon without a valid serial number or tag would be *prima facie* evidence of a violation, a fact that greatly increases the power of inspections.

Regarding the second task, it seems likely that most storage bunkers do not contain objects that could be mistaken for nuclear weapons. Exceptions undoubtedly exist, however, and so procedures could be developed to demonstrate that an object is not a nuclear weapon. For objects that are not sensitive, such as an empty canister, this could be done by visual inspection. Otherwise, a simple neutron detector on one side of the canister and a weak neutron source on the other side could be used to confirm that the canister does not contain a nuclear weapon. This is similar to the procedure worked out in START I to confirm that a cruise missile is not armed with a nuclear weapon. The neutrons emitted by the plutonium in a weapon are easily detectable unless the weapon is shielded; the neutron source can be used to determine whether the container absorbs neutrons.

Visual inspection, supplemented by simple radiation measurements, would be a straightforward way to build confidence in weapon declarations. This method is not foolproof, however. It might not be able to detect weapons that do not contain plutonium, because the rate of neutron emission from highly enriched uranium (HEU) is very low. (The use of a detector in conjunction with a low-intensity neutron source would indicate that the object is suspicious, however.) Moreover, some nonweapon objects that may be stored in bunkers (e.g., weapon components, radioisotope thermal generators, or nuclear-explosive-like objects) might emit enough neutrons to be mistaken for a weapon. States may therefore judge that a formal agreement would require a higher degree of assurance that objects declared as weapons are indeed genuine weapons, and that other objects are not weapons. Two general approaches to this problem—the "template" and the "attribute" approaches—are outlined in Box 2-4. We believe, however, that these relatively complicated procedures are better suited for identifying and verifying the authenticity of weapons prior to dismantling than for inspections to confirm declarations.

CONTINUOUS MONITORING OF WEAPON STOCKS

The previous section discussed the use of sampling to confirm periodic declarations of weapon stocks. In some cases, parties might wish to have additional assurance that certain weapons were being kept in a specified location; for example, there could be large numbers of inactive weapons that were retired and awaiting dismantling, or large numbers of nonstrategic weapons that, by agreement, were required to be kept in storage. Transparency measures that provide continuous information about the status of such weapons could help address concerns about their possible redeployment, diversion, or theft.

Several concepts for the continuous monitoring of weapons in storage facilities have been considered, ranging from perimeter-portal systems that monitor the flow of items into and out of a facility to systems that continuously monitor the status of items within a facility. In a perimeter-portal monitoring system, a secure perimeter forces all facility traffic though monitored portals. The perimeter typically is a fence established by the inspected party, the integrity of which is monitored by the inspecting party with various sensors (e.g., cameras, motion/intrusion detectors, acoustic and seismic sensors) mounted just outside the fence, supplemented by occasional foot or vehicle patrols. The portal is typically the facility's main gate. The inspecting party monitors the portal for the possible entry and exit of controlled items—in this case, nuclear weapons and weapon components. In this way, the inspecting party can continuously monitor changes in the inventory of a facility with only occasional access to its interior (e.g., to establish the initial inventory).

Continuous perimeter-portal monitoring systems were first established at Votkinsk, Russia, and Magna, Utah, to verify the INF Treaty's ban on the production of the SS-20 and Pershing II mobile intermediate-range missiles. Each party was allowed to perform around-the-clock monitoring for 13 years, including measuring all vehicles entering and leaving the facilities and inspecting any vehicle large enough to contain a prohibited item. Because the Russian SS-25 ICBM, which also was produced at Votkinsk, has a stage that is similar in size to the prohibited SS-20, all SS-25 missile canisters leaving the plant were also subject to radiographic imaging to confirm their identity. Building on the successful INF experience, the START I Treaty extended perimeter-portal monitoring to two missile assembly facilities in Russia and Ukraine to help verify declarations of the total number of mobile ICBMs. Although similar systems and procedures could be applied to monitoring the perimeter of a weapon storage facility, portal monitoring is more challenging in this case because nuclear weapons are much smaller and more easily disguised than ballistic missiles.

As with the weapon storage inspections described above, portal monitoring can be divided into two basic tasks: (1) confirming that objects passing through the portal that are declared to be weapons are, in fact, genuine weapons, and (2) confirming that no other undeclared weapons have entered or left the facility. The first task is fairly straightforward. Facility management would notify the inspecting party that a certain number of weapons would be delivered to or removed from the facility at a given time, and inspectors would confirm the authenticity of a random sample or all of the weapons as discussed above, or using template or attribute identification.

The second task is to confirm that weapons are not being smuggled into or out of the facility, either whole or in parts. In most cases, visual inspection of vehicles combined with neutron and gamma-ray detectors at the portals would be sufficient to provide assurance against the movement of undeclared weapons. If the visual inspection revealed a container large enough to hold a shielded weapon, a low-intensity neutron or gamma-ray source could be placed on one side of the container and a detector on the other side to determine whether it might conceal the presence of a nuclear weapon. The portal could be equipped with radiography equipment to scan selected vehicles, but this would add substantially to the cost of the system unless it significantly reduced the need for human inspectors. If ambiguities arose, the burden of proof would be on the inspected party to demonstrate that objects and vehicles passing through the portal do not contain undeclared nuclear weapons or weapon components.

Although perimeter-portal systems in the past have required the continuous presence of inspectors (the INF and START I treaties allowed up to 30 inspectors), remote monitoring technologies could reduce the need for a continuing human presence and thus the cost of operating such systems; for example, data from cameras and other sensors that confirm the integrity of a perimeter can be monitored remotely, requiring only periodic visits to test, maintain, or repair the equipment. If there were little vehicle traffic aside from weapon movements that are scheduled well in advance, even portal monitoring could be accomplished with little or no permanent on-site presence, provided provisions were made for rapid response to the loss of remote monitoring capability and for a freeze on all vehicle traffic until the monitors were restored.

A promising variation on this concept is remote monitoring of individual storage bunkers or vaults. One could, for example, mount a variety of sensors—video and infrared cameras, motion sensors, radiation detectors, laser break-beams, vehicle detectors, and the like—outside the access doors to each bunker to detect any attempt to enter and remove weapons. The sensor packages would be equipped with an uninterruptible power supply and housed in enclosures that prevented undetected tampering; sensor data would be encrypted, stored and also transmitted securely via telephone lines and/or satellite to a remote monitoring station. Similar systems are now used by the International Atomic Energy Agency (IAEA) for remote monitoring of the status of nuclear facilities and stocks of nuclear material. Except in an emergency, the inspected party could be required to give several days notice prior to opening the bunker doors, to allow inspectors to arrive and confirm any movement of weapons in or out of the facility.

Alternatively, one could remotely monitor the interior of weapon storage bunkers. The prototype "magazine transparency system" developed at Los Alamos National Laboratory uses a combination of commercially available, off-the-shelf sensors to maintain automatically an inventory of a bunker and detect any movements of weapons.[23] During an initial inspection, each weapon storage container is covered with a blanket that contains magnets and a radio frequency identification tag. A video camera detects any scene change and a gaussmeter detects changes in the magnetic field caused by movements of the magnetic blanket; interrogation of the radio frequency tag provides inventory information and additional motion detection. A computer monitors all sensors and triggers an alarm message if movement is detected;

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[23] James E. Doyle and Roger G. Johnston, "Integrated Facility Monitoring System (IFMS) and Magazine Transparency System (MTS)," Report LA-UR-00-1671 (Los Alamos, NM: Los Alamos National Laboratory, March 2000).

otherwise it sends an "all ok" signal. Measures can be taken to counter the use of intense, externally produced magnetic fields to spoof such systems.

In addition to monitoring facility inventories, one might also wish to monitor or track the movement of weapons between facilities; for example, parties might desire assurance that particular weapons removed from deployment sites were delivered to monitored storage, or that weapons removed from storage were delivered to dismantling facilities. Establishing the authenticity or provenance of items, tracking their movements between facilities, and confirming that they have not been tampered with is sometimes referred to as a "chain of custody."

The least intrusive way to maintain a chain of custody involves the use of tags and seals. Tags uniquely identify objects; seals are tamper-indicating devices that prevent undetected access (see Box 2-3). Tags and seals must be difficult to remove, alter, or counterfeit without detection, and they must not compromise the safety, security, or reliability of the item to which they are attached or collect information not needed for monitoring. A wide variety of tags and seals have been developed, ranging from bar codes and tamper-indicating tape to electronic tags and seals. Tags and seals are used routinely by the IAEA to safeguard civilian nuclear materials, and were used by the U.N. Special Commission on Iraq to track items that could be used for both civilian and military purposes. Current technology makes available a number of approaches to tag and seal applications that would be extremely difficult to defeat without detection and that should not create legitimate problems for any party.

Chain-of-custody monitoring could begin when a weapon is removed from a delivery vehicle or operational deployment area and placed in a container that is tagged and sealed, or when the authenticity of a weapon is confirmed using a template or an agreed set of attributes. When the weapon enters or leaves a facility, the integrity of the tag and seals would be checked and its identity confirmed using the tag. This procedure could be done by inspectors at the portal to a facility or, if electronic tags and seals were used, the identity and integrity of tags/seals might be checked automatically whenever the canister enters or leaves a monitored facility or storage bunker. The integrity of tags and seals could even be monitored remotely and continuously; for example, Los Alamos National Laboratory has developed a prototype tag and seal that uses a low-cost, off-the-shelf video camera and transmitter to provide remote, continuous surveillance of its integrity as it is moved between facilities.[24] This type of device could be used to monitor weapons as they are transferred from storage to dismantling facilities, and as they move through the dismantling facility.

CONFIRMING WEAPON ELIMINATION

Declarations of weapon stocks and transparency and monitoring measures to confirm their accuracy serve to establish baseline inventories of nuclear weapons. Extending transparency measures to weapon dismantling facilities could help confirm agreed or stated reductions in these inventories and provide assurance that weapons removed from the declared inventory were not simply moved to undeclared locations. There are several options for increasing the transparency of weapon dismantling operations, which draw on the technologies and procedures introduced above. In general, options that provide a higher degree of confidence that weapons have been dismantled come at the cost of greater intrusiveness and impact on normal operations, and require more effort to protect sensitive weapon design information.

Monitored Storage of Weapons and Components

The least intrusive option would involve monitoring the storage of weapons and weapon components, without monitoring the dismantling process itself. The inspected party would declare that a particular weapon was slated for dismantling. The inspecting party could confirm that this weapon was removed from a monitored storage facility; tags and seals on the weapon container could be used to confirm that the same weapon was delivered to the dismantling facility. After the weapon was dismantled, the inspected party would deliver its key components—the pit and secondary assembly—to a monitored storage facility, at which point the weapon would be considered eliminated. The inspecting party could confirm, using templates and attributes, that weapons going into the facility and components coming out were authentic. As before, a system could be designed such that inspection of a relatively small sample could be sufficient to provide a high degree of confidence in the authenticity of all weapons and components. Inspection of a random sample of 22, 45, or 230 objects could detect, with 90 per-

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[24] Eric R. Gerdes, Roger G. Johnston, and James E. Doyle, “A Proposed Approach for Monitoring Nuclear Warhead Dismantlement,” *Science and Global Security* 9 (2001), p. 113. Available as of January 2005, at: http://www.princeton.edu/~globsec/publications/pdf/9_2gerdes.pdf.

cent probability, violations equal to 10, 5, or 1 percent of the total number of objects; doubling the number of inspections increases the probability of detection to more than 99 percent.[25]

By itself, this process would not, however, provide high confidence that the declared weapons were dismantled; for example, one could not rule out the possibility that the weapon components delivered to the monitored storage facility were recovered from other (perhaps obsolete) weapons, taken from existing component stores, or newly produced from existing stocks of plutonium and HEU. To rule out such possibilities, the inspecting party would need to have confidence that the components were recovered from the weapon that was delivered to the dismantling facility. This might be accomplished with fission product tagging, pit stuffing, or template or attribute matching.

Fission Product Tagging

It has been suggested that the inspecting party might "tag" weapon components while they are still inside the weapon by irradiating the weapon with neutrons before it is delivered to the dismantling facility.[26] This would induce fissions in the plutonium and uranium components, giving them a characteristic gamma-ray signature that could be analyzed after the weapon is dismantled to determine whether it is consistent with the irradiation. A relatively large neutron flux is required to produce a measurable signature over the period required to dismantle a weapon. In addition, the signature probably could be spoofed.

Pit Stuffing

Another approach to component tagging is known as "pit stuffing."[27] As discussed in Box 2-1, nuclear weapons may use hollow-

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[25] If the sample size is small compared to the total number of objects (e.g., less than 10 percent), the probability of selecting an object in violation of the declaration depends only on the size of the sample and not the total number from which the sample was chosen. The general formula in this case is $P = 1 - (1-F)^n$, where F is the fraction in violation, n is the sample size, and P is the probability that the sample contains at least one object in violation. If the sample size is a larger fraction of the total number of objects, the probability of detection will be higher; see Footnote 18.

[26] Gerald P Kiernan, et al., "Interim Technical Report on Radiation Signatures for Monitoring Nuclear-Warhead Dismantlement." JEP-009. Work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48 (April 17, 1997).

[27] Matthew Bunn, "'Pit-Stuffing:' How to Disable Thousands of Warheads and Easily Verify Their Dismantlement," *F.A.S. Public Interest Report* (March/April 1998). Available as of January 2005, at: http://www.fas.org/faspir/pir0498.htm#bunn.

boosted pits—a spherical shell of plutonium penetrated by a thin "pit tube" to admit the tritium-deuterium boost gas from an external reservoir. For such weapon designs, the inspected party could insert something into the pit that could not be removed without disassembling the pit, but which would not unduly complicate the later processing of the pit or disposition of the plutonium. Suggestions have included inserting a fragile wire that would fragment inside or epoxy or some other substance. This could have the additional benefit of rendering the pit and the nuclear weapon immediately unusable, since the wire would prevent a nuclear explosion.[28] The pit tube presumably is accessible through a maintenance port in the weapon, because the radioactive decay of tritium, with a half-life of 12 years, requires regular replacement of the external reservoirs. The inspected party could perform the pit-stuffing operation, and the inspecting party could confirm on a sampling basis that the pits were stuffed, both before and after the weapons are dismantled, by taking x-ray images of a small part of the pit or by incorporating tiny amounts of a gamma-ray emitter (e.g., cobalt-60) into the wire and using a high-resolution gamma-ray detector to confirm its presence inside the pit. Alternatively, one might use the pit tube to attach a small tag to the pit (e.g., using wires that spring open in the hollow pit), that could not be removed without detection.

Template or Attribute Matching

Weapon components also might be associated with weapons using templates or attributes (see Boxes 2-4, 2-4A, and 2-4B); for example, the inspected party could present the separated components for templating along with the fully assembled weapon, and the templates could then be used to confirm, on a sampling basis, that the components placed in storage correspond to the type of weapon delivered to the dismantling facility. As always, the challenge would be knowing whether the items presented for templating were authentic. This could be determined by careful monitoring, as described below in "Monitoring Dismantling Operations," of the dismantling of a randomly selected weapon of each type and using this weapon and its components for the templates. Alterna-

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[28] The idea was originally developed as a method of safing weapons by using a wire that was retracted as part of the arming process. Of course, in that case the wire was designed to be easily withdrawn.

tively, one could determine whether certain attributes of the weapon match those of the corresponding pit or secondary assembly, such as the mass and age of plutonium in the pit or the mass and enrichment of uranium in the secondary assembly.

Perimeter-Portal Monitoring

A straightforward alternative for monitoring weapon elimination would be to equip each dismantling facility with a perimeter-portal monitoring system, similar to that described above for weapon storage facilities. Weapons to be dismantled would arrive at the portal, where their identity and authenticity could be confirmed using tags and seals and, at least on a sampling basis, templates and attributes. Weapons would be considered dismantled when the corresponding pits and secondary assemblies exit the portal for shipment to a component storage facility. Radiation detectors and other equipment and procedures could assure that no undeclared weapons or weapon components could pass through the portal without detection. Inspections of the facility might be permitted before and after dismantling campaigns to provide assurance that large stocks of weapons or components were not accumulating inside. Such facilities are very large, however, and it would be nearly impossible to obtain high confidence that weapons or components were not hidden somewhere inside.

The primary disadvantage of perimeter-portal monitoring is the relatively high cost of establishing and operating the system. Weapon dismantling facilities have very large perimeters; presumably, measures to guard against covert tunnels and passageways would be wanted. The portals would need to be heavily instrumented and would require the continuous on-site presence of inspectors to sift through the large volume of traffic in and out—including many items of a sensitive nature—and this could interfere with the normal operation of the facility. On the other hand, the United States and Russia have acquired extensive experience with perimeter-portal monitoring of missile production and assembly facilities under the INF and START treaties, and perimeter-portal monitoring of weapon dismantling facilities could help greatly in monitoring weapon assembly and remanufacture (see below).

Monitoring Dismantling Operations

A third option would involve monitoring weapons as they move through the dismantling facility. This could be done—on a continuous basis with remote monitoring equipment or on a sampling basis with on-site inspectors—by monitoring the bays and cells in which the key disassembly operations occur: the separation of the nuclear-explosive device or "physics package" from other weapon components, the subsequent separation of the primary and the secondary assembly, and the separation of the pit from the primary.

Monitoring could begin by escorting inspectors into the empty bays and cells to confirm that there were no hidden entrances and, using radiation detectors, that there were no hidden weapons or stocks of NEM. Inspectors could then monitor the entrance, or sensors could be installed at the bay or cell doors similar to those described above for continuous remote monitoring of weapon storage bunkers. When a weapon container arrived at the entrance, the inspectors or sensors could confirm its identity and authenticity by checking the tags and seals applied earlier (at a storage facility or the entrance to the dismantling facility). After authentication, the tags and seals could be removed and the weapon moved into the bay or cell. Here the first set of disassembly operations could be performed by the inspected party and the various components placed into one or more containers. Containers declared by the inspected party to contain NEM could be tagged and sealed as they left the bay or cell (by inspectors, or by the inspected party under remote observation). Other containers could be checked for the presence of NEM and those without it would not need to be subject to control thereafter. Controlled items could then be tracked to the next bay or cell and the process repeated, until the weapon was completely disassembled and the pit and the secondary assembly were in tagged and sealed containers, ready to be shipped to a monitored storage facility. The inspection protocol could include time limits for each disassembly operation and movements between bays and cells, as well as inspections of bays and cells between dismantling campaigns. With proper design, this type of monitoring system could give a high degree of confidence that particular weapons had been dismantled.

CONFIRMING WEAPON REMANUFACTURE AND ASSEMBLY

Along with monitoring weapon inventories, it would be logical to monitor possible additions to these inventories as well. Transparency measures to confirm the dismantling of weapons would be of limited value without complementary measures to monitor the assembly of new weapons to provide assurance that no new undeclared weapons were being built. Measures to monitor nuclear weapon components and other inventories of plutonium and HEU and to confirm that plutonium or HEU was not being produced for weapons purposes could provide some assurance that significant numbers of new weapons could not be built without detection. As discussed in Chapter 3, however, it is difficult to establish accurately the baseline inventory of these materials and to rule out the possibility of hidden stockpiles that could be used to produce nuclear weapons. It therefore would be important to monitor weapon assembly facilities for the production of new weapons as well as the elimination of existing weapons.

This task would be simple and straightforward if the fabrication of all nuclear weapons could be ended. But weapons have a finite shelf life due to the aging and decay of high explosives and other materials, and so maintaining a nuclear stockpile over the long term requires the assembly or at least the remanufacture of weapons. Weapons may also be assembled to replace those dismantled or destroyed in routine (non-nuclear) reliability testing or to fix safety and reliability problems that may be uncovered in a particular weapon type. This would be true even if there were substantial reductions in the total stockpile of weapons.

Requirements for weapon assembly are likely to be modest as a result of reductions in weapon inventories and the absence of new types of nuclear weapons. The Bush Administration has indicated that the total U.S. stockpile will be reduced to fewer than 5,000 weapons over the next decade.[29] If U.S. weapons are remanufactured every 45 to 60 years,[30] the average rate of assembly would be

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[29] Colin L. Powell, "Remarks on the US-Russian Strategic Offensive Reductions Treaty," Testimony before the Senate Foreign Relations Committee (July 9, 2002). Available as of January 2005, at: http://www.state.gov/secretary/rm/2002/11743.htm. See also Linton F. Brooks, "Report to Congress on the Revised Nuclear Warhead Stockpile Plan," Unclassified Executive Summary. NNSA Press Release, June 3, 2004, and Linton F. Brooks, "U.S. Nuclear Weapons Policies and Programs," Remarks presented at the Committee on International Security and Arms Control Symposium: Post-Cold War U.S. Nuclear Strategy: A Search for Technical and Policy Common Ground. August 11, 2004. Available as of January 2005, at:
http://www7.nationalacademies.org/cisac/Brooks_Presentation.pdf. "In May of this year, the President approved a stockpile plan that will dramatically reduce the current stockpile. As a result of the President's decision, by 2012, the United States' nuclear stockpile will be cut almost in half and will be the smallest it has been in several decades" p. 5.

[30] This corresponds to the current estimate of the minimum lifetime of U.S. plutonium pits. See "Plutonium Aging: Implications for Pit Lifetime," Appendix G, Modern Pit Facility Draft Environmental Impact Statement National Nuclear Security Administration (June 4, 2003), G-63. Available as of January 2005, at: http://www.mpfeis.com/.

about 100 per year. Even if, as often assumed, the average lifetime for Russian weapons is two or three times shorter, the assembly rate need not be greater than a few hundred per year. These rates are roughly one-tenth the estimated capacity of existing U.S. and Russian assembly facilities. Reducing the capacity of these facilities could therefore be an important confidence-building measure. (In the case of the United States, the limiting factor at present would be the capacity to produce new plutonium pits, if necessary.) In the short term, one could install seals and monitoring devices on bay and cell doors to confirm that they had not been opened; in the longer term, excess bays and cells or entire facilities could be dismantled. The problem is becoming simpler in Russia, which has reduced the number of large assembly facilities in operation from four to two.

Parties might accommodate the need to continue weapon manufacture simply by agreeing to declare at regular intervals the number of weapons assembled and to permit transparency measures to confirm these declarations. Parties might even agree to permit only the remanufacture of weapons in the existing stockpile or the replacement of existing weapons on a one-for-one basis. In this case, transparency measures could be designed to confirm that a nuclear weapon had been removed from the stockpile for every new or remanufactured weapon added to the stockpile.

Some may argue that transparency measures for weapon remanufacturing might reveal vulnerabilities in the force. If, for example, Russia observed that the United States was rebuilding a particular class of weapons, it might conclude that this weapon type suffered from a major reliability problem. Russia would be likely to discover the existence of such a problem without the benefit of transparency measures, however. This knowledge seems unlikely to affect U.S. security significantly in any case since the United States plans to continue deploying several different weapon types.[31] This is not a problem at the force levels permitted in the Moscow Treaty, but maintaining some diversity in weapon types would become important at much lower levels. Moreover, any imagined vulnerability could be dispelled quickly if the United States maintained an appropriate capacity to remanufacture nuclear

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[31] The Treaty of Moscow limits the United States to 2,200 operationally deployed nuclear weapons. It is expected that the United States will maintain 500 weapons on Minuteman III missiles, at least 260 bombs and cruise missile weapons on B-52H and B-2 bombers, and up to 1,440 weapons on Trident II missiles. The United States plans to maintain two types of nuclear weapons for each delivery vehicle.

weapons. On balance, we believe that greater transparency for stockpile stewardship and remanufacturing activities of potential adversaries is more likely to prove a valuable confidence-building measure than a security concern.

If transparency measures were applied to weapon assembly, they would need to be tightly integrated with the measures adopted for weapon dismantling. If dismantling was confirmed with inspections or automatic tracking of weapons and weapon components between bays and cells within the assembly facility, weapons to be remanufactured or replaced could be tracked in exactly the same manner. The only difference is that new weapon components might enter certain bays and cells, and the end product would be a complete weapon and perhaps the old components.

If perimeter-portal monitoring systems were installed at weapon assembly facilities (e.g., using existing perimeter fences and gates), these could be used to confirm weapon remanufacture as well as dismantling. When a weapon arrived at the portal, for example, the inspected party could declare whether it was to be dismantled, remanufactured, or replaced. For weapons to be remanufactured or reassembled using the same pit and secondary assemblies, one would need only to confirm that the same number of weapons leave the facility; one could, with templates, confirm that the remanufactured weapons are of the same type as those that entered. For weapons that were being replaced or assembled with new components, the old weapons could be dismantled and the components shipped to a storage facility. New pits and secondary assemblies that entered the assembly facility for the declared purpose of assembling replacement weapons could be appropriately tagged and sealed before leaving the facility.

Another useful approach to building confidence is through open technical collaborations and exchanges related to maintaining confidence in the safety and reliability of existing stocks of nuclear weapons and minimizing the remanufacture of weapons. Conferences for scientists and engineers involved with stockpile stewardship could help to clarify the range of technical issues being addressed and the capabilities available for addressing these.[32] Exchange of unclassified information regarding the properties of relevant materials—or their surrogates—could offer confidence that key issues in stewardship are being addressed by all parties,

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[32] For example, although problems with visas have complicated the process substantially, it has become typical to have a significant Russian presence at the annual Institute for Nuclear Materials Management conferences.

for example. Even if the actual data were not shared, joint monitoring of experiments could also reassure the parties involved that no violations take place (e.g., no nuclear explosion yield during a period of test moratorium). Although some of the research discussed might be only distantly related to the most sensitive areas of work for one side or the other, the understanding provided to all sides by comparing notes at the unclassified level of basic research could enhance other confidence-building measures.

TRANSPARENCY MEASURES FOR NEM COMPONENTS

Because the pits and secondary assemblies that remain after weapons are dismantled could be used to build new weapons, the storage and ultimate elimination of these components could be subject to transparency and monitoring measures similar in nature to those applied to nuclear weapons. Fabricated NEM components are discussed here because many of the transparency measures and technologies discussed above for nuclear weapons could be applied with little modification to these components. Like nuclear weapons, details of component design are sensitive and must be protected. Moreover, unlike bulk NEM, which is discussed in the next chapter, pits and secondary assemblies are discrete objects that could be subject to item accounting.

Declarations

As with nuclear weapons, increased transparency logically would begin with a declaration of weapon component inventories. In the case of a formal declaration, parties would first need to agree on a definition of "weapon component," such as, for example, "any object or item that contains NEM metal and that has been used or is in a form designed for use in a nuclear-explosive device, but is not part of an assembled device."

Parties could declare the total number of pits, secondary assemblies, and other components or the total mass of plutonium and HEU contained in these components. This could help build confidence by limiting worst-case assessments of the capacity of other parties to rapidly reconstitute dismantled nuclear weapons. Component inventories could be further disaggregated by weapon type and current location, and ultimately into an itemized list giving the serial number, location, and corresponding weapon type of each component or container. Even if a complete itemized inventory were considered highly sensitive, it could be safely exchanged in encrypted or digest form and its accuracy confirmed through inspections of a random sample of the items.

Monitored Storage

Declarations of component inventories could be confirmed using the techniques discussed above for nuclear weapons, through a combination of occasional inspections and continuous monitoring of declared storage facilities. The arrangements for the Russian fissile material storage facility at Mayak may be able to serve as a model for such initiatives. In exchange for U.S. financial assistance to construct the Mayak facility, Russia agreed to allow transparency measures to confirm that material placed in the facility was taken from dismantled nuclear weapons, that material in the facility is safe and secure, and that any material removed from the facility was not used for nuclear weapons.

The prototype attribute identification system described in Box 2-4B was developed to confirm that plutonium pits placed in the Mayak facility are authentic; similar systems could be developed for secondary assemblies and other NEM components. Russia has announced that the materials placed in the Mayak facility will be reshaped to remove sensitive weapon design information, ostensibly to facilitate IAEA inspection of the material (see Chapter 3). Although this reshaping would make the materials somewhat less immediately reusable for nuclear weapons, it would also reduce confidence that the material came from a dismantled nuclear weapon. Confidence would be higher if authentication were performed soon after a weapon is dismantled, while the pit and secondary assembly were still in their original forms.

NEM components are typically stored in special sealed canisters. At Mayak, the canisters are to be tagged with a unique identifier and entered into a computerized control and accounting system. According to the U.S. General Accounting Office, a 1999 draft of the Mayak transparency agreement contained the following provisions:

> U.S. monitors would be allowed to inspect Mayak six times a year and utilize data generated by Mayak's material control and accounting system. U.S. monitors would be allowed to spend at least 5 days to conduct the initial inspection. During each inspection, they would be allowed to download recorded data from sensors used by the Russians to identify, scan, and track each container as it passes

> through Mayak's unloading and incoming control rooms. Annually, U.S. monitors would be able to select randomly up to 120 storage shafts and verify the identifying tags on the containers in those shafts against Mayak's records. U.S. monitors would have the right to scan one container from each of the selected shafts to determine its contents. Russia also would be required to inventory a random number of containers twice a year with U.S. participation.[33]

Provisions such as this, if ultimately accepted, could provide a high degree of confidence that the data contained in the declaration or control and accounting system are accurate and that components have not been removed from the facility. One hundred and twenty inspections under such rules would provide more than a 99 percent chance of detecting violations involving as few as 4 percent of the canisters. As of early 2005, however, the United States and Russia have not been able to agree on what monitoring measures are to be applied, so it is uncertain how comprehensive any eventual measures may be. Chapter 3 discusses the current situation in more detail.

Component Elimination

Nuclear weapon components are eliminated when they are mechanically and/or chemically converted into bulk materials. Transparency measures to confirm the conversion of HEU weapon components into bulk materials were developed in connection with the HEU purchase agreement, under which the United States agreed to purchase over a 20-year period 500 tons of Russian HEU from dismantled nuclear weapons in the form of low enriched uranium (LEU).[34] The main steps in this process are as follows:

- the HEU weapon component is machined into metal shavings;
- the metal shavings are oxidized and the resulting oxide chemically purified;

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[33] U.S. General Accounting Office, "Weapons of Mass Destruction: Effort to Reduce Russian Arsenals May Cost More, Achieve Less Than Planned," NSIAD-99-76 (Washington, DC: General Accounting Office, April 13, 1999). Available as of January 2005, at: http://www.gao.gov/archive/1999/ns99076.pdf.

[34] Throughout this report "ton" refers to metric tons. One metric ton is 2,205 pounds, roughly 10 percent more than an English ton.

- the HEU oxide is chemically converted into uranium hexafluoride;
- the HEU hexafluoride (~ 90 percent uranium-235) is blended with LEU hexafluoride (1.5 percent uranium-235);[35] and
- the resulting LEU hexafluoride (about 4 percent uranium-235) is loaded into cylinders and shipped to the United States for use in the fabrication of fuel for commercial nuclear power reactors.[36]

Agreed transparency measures include on-site monitoring and reviews of the material control and accounting system documents by U.S. inspectors at the four Russian facilities involved in this process. Russia has similar inspection rights in the United States to confirm that the LEU product is used in the manufacture of reactor fuel. At each stage inspectors can inspect equipment, observe the processing of material, and use portable equipment to measure the enrichment of the uranium. At sites where HEU is blended, the "blend-down monitoring system" automatically and continuously measures the flow and enrichment of the HEU and LEU feed and LEU product flows. These transparency measures provide high confidence that the LEU delivered to the United States was derived from HEU.

By coupling this process with an attribute or template identification system to confirm that the HEU delivered to the facility was in the form of genuine weapon components, one could have similarly high confidence that these components had been eliminated. If such a system had already been used to identify weapon components at the dismantling or storage facility, it would only be necessary to check the integrity of the tags and seals on the canisters when they are delivered to the conversion facilities. Tags and seals could also be used to ensure a "chain of custody" on material that is moved from one facility to another in the conversion process.

The United States and Russia have agreed in principle to dispose of 34 tons of weapon-grade plutonium apiece, but progress toward implementation has stopped. It is expected, however, that

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[35] Low-enriched uranium (1.5 percent U-235) is used for blending instead of natural or depleted uranium in order to meet standards on the concentration of U-236 in the LEU product.

[36] A more detailed description, with photos of the major facilities and operations, may be found on the USEC Web site available as of January 2005, at: http://www.usec.com/v2001_02/HTML/megatons_stepbystep.asp.

transparency measures similar to those described above would be required for the plutonium disposition agreement. Parties could confirm the authenticity of weapon-grade plutonium delivered to the conversion facility using the attribute method described in Box 2-4B, and monitor the conversion of the plutonium into oxide and the fabrication of the plutonium oxide into reactor fuel (or mixing with high-level waste and subsequent vitrification). Plutonium disposition is covered in more detail in Chapter 3.

Component Fabrication

A complete accounting system would also include additions as well as subtractions to the inventory of key weapon components. Future requirements for component manufacture are largely unknown. Lifetime estimates for U.S. pits and secondary assemblies are in excess of 50 years, in which case fewer than 100 per year would have to be fabricated to maintain a stockpile of 5,000 weapons, and only 10 per year for a stockpile of 500. The United States currently is studying options for constructing a "modern pit facility" that would process old pits and use the plutonium to fabricate new pits. Transparency measures could be negotiated for such facilities that allowed other parties to confirm the rate at which pits were processed and new pits were fabricated. Conceptually, at least, this would be most straightforward with a perimeter-portal monitoring system.

CONCLUSIONS

This chapter has reviewed and assessed the potential of a range of technical tools and methods to monitor all the phases of the nuclear weapon life cycle, from assembly to storage to deployment to dismantling and reuse or elimination. Past and current arms control agreements have provided significant practical experience in the design and implementation of monitoring systems for nuclear weapon delivery systems, including their production and storage. In addition, since the end of the Cold War, U.S. and Russian nuclear weapons laboratories, as part of their broader program of joint threat reduction activities, have carried out substantial cooperative work on extending these arrangements directly to nuclear weapons and their components.

We conclude that:

1. A range of transparency and monitoring measures are available that could be applied to declared stocks at declared sites to cover all the stages of the nuclear weapon life cycle, including
   - declarations of nuclear weapon stocks at progressively increased levels of detail, from all nuclear weapons to declarations by type, status and associated delivery vehicle, to declarations for each weapon by serial number, weapon type, status, and current location;
   - declarations of the name and location of all facilities at which nuclear weapons are currently deployed, stored, assembled, maintained, remanufactured, dismantled, or other otherwise handled, along with detailed information about each site and its operating history;
   - continuous monitoring of weapon stocks at facilities at all stages throughout the nuclear weapon life cycle, either with personnel on site or remotely;
   - confirmation of weapon remanufacture and assembly as well as weapon elimination; and
   - provisions for routine on-site inspections at declared facilities to confirm declarations and any updates, as well as for inspections of both declared and suspect sites in the event of detection of suspicious activity or unexplained discrepancies.

Similar measures could be applied to nuclear weapon components.

2. The necessary technical tools are either available today, or could be in hand with some additional development, to support transparency and monitoring measures for declared stocks at declared sites throughout the nuclear weapon lifecycle. These tools draw on the following techniques:
   - Developments in cryptography now widely used in banking and other commercial transactions offer a way to exchange, in a limited and controlled but still very useful way, sensitive information about nuclear weapons that countries would not be willing to share more openly and comprehensively because of security concerns.
   - Methods are available to examine from a short distance the radiation from a nuclear weapon or to interrogate a declared weapon container with an ex-

  ternal radiation source. The radiation signature can be matched against "templates" of actual nuclear weapons signatures, or some portion of the radiation signatures can be singled out to identify "attributes" that confirm the object is indeed a weapon. These techniques permit identification without revealing sensitive weapon design information.
  - A wide array of tags and seals, ranging from bar codes and tamper-indicating tape to electronic tags and seals, can be applied to containers and storage rooms for weapons and interrogated to check their status.
  - Monitored perimeter-portal systems, which exploit radiation and other distinctive signatures, can be installed and operated to confirm that what enters and leaves any given facility is what it is supposed to be.
  - Facilities and areas within facilities can be equipped with appropriate sensors and accountability systems to monitor declared activity and detect undeclared activity, the recordings from which can either be examined during periodic inspections or uploaded via the Internet or satellites for transmission to a monitoring center.
3. Depending on the design of the system, cooperative application of these transparency and monitoring measures would make it possible to confirm the accuracy of declarations of weapon stocks and to monitor weapon storage, assembly, and disassembly at declared facilities while protecting sensitive weapon design information. (The degree of confidence that can be obtained about the completeness of declarations—that no secret stocks of weapons exist at undeclared facilities—is addressed in Chapter 4.)
4. Some of the less intrusive measures, in particular declarations of current weapons stocks .or of plans for future changes to those stockpiles, can have value in their own right as confidence-building measures. These measures could be undertaken unilaterally or through formal
5. In general, tools and measures that provide a higher degree of confidence come at the cost of greater intrusiveness and potential impact on normal operations. They also require more effort to protect sensitive weapon design information.

They are therefore more suited to formal agreements where the rules for the system's operation can be agreed upon, including provisions for resolving questions or clarifying ambiguities. Experience suggests, however, that reaching such agreements can be a difficult and protracted process.

6. Even a modest subset of the measures outlined here could provide a degree of openness concerning weapon stockpiles and a framework for access to weapon sites that would greatly ease the difficulties of cooperation to improve security of nuclear weapons everywhere against theft or unauthorized use. For the more demanding purpose of monitoring agreements to control or reduce the stocks of nuclear weapons held by nuclear weapon states, the more intrusive measures would also be required.

BOX 2-1

What Is a “Nuclear Weapon”?

The terms “nuclear warhead” and “nuclear weapon” have not been defined with much precision in existing treaties. The Nuclear Non-Proliferation Treaty (NPT) restricts the transfer or acquisition of “nuclear weapons or other nuclear explosive devices” but offers no definition for this term, nor do the treaties that prohibit the deployment of nuclear weapons in space or on the seabed. In the START I Treaty, the term “warhead” is defined simply as “a unit of account used for counting,” and earlier U.S.-Soviet arms control treaties used the term without definition.

The most complete definition is given in the 1985 South Pacific Nuclear Free Zone Treaty (Treaty of Rarotonga) and the 1996 African Nuclear-Weapon-Free Zone Treaty (Treaty of Pelindaba): “‘nuclear explosive device’ means any nuclear weapon or other explosive device capable of releasing nuclear energy, irrespective of the purpose for which it could be used. The term includes such a weapon or device in unassembled and partly assembled forms, but does not include the means of transport or delivery of such a weapon or device if separable from and not an indivisible part of it.” This definition is not entirely satisfactory, inasmuch as “capable of releasing nuclear energy” remains undefined, but it underscores the importance of understanding at what point a weapon is considered dismantled and no longer counted as a “nuclear weapon.”

Like past treaties, agreements dealing with weapon transparency measures could simply refer to “nuclear weapons or other nuclear-explosive devices” without adopting a more detailed definition. As discussed in this chapter, there are several approaches for confirming, with varying degrees of confidence, whether or not an object is a weapon. In this way, the term ”weapon” would be defined operationally by the objects that are declared to be weapons and the techniques used to confirm that an object is a weapon.

All nuclear weapons include a fission explosive device, which creates a divergent fission chain reaction by rapidly assembling a supercritical mass of nuclear-explosive material (NEM)—plutonium or highly enriched uranium (HEU). (See Chapter 3 and

Appendix A for a further technical discussion of NEM.) Assembly can be accomplished by "implosion," in which chemical explosives are used to compress a sphere or hollow shell of NEM, or by "gun assembly," in which one mass of NEM is fired like a bullet into another mass of NEM. Thus, a nuclear explosive might be defined as "any device containing high explosive or propellants and nuclear-explosive material and capable of producing a nuclear explosion."*

The "Little Boy" device used on Hiroshima and the nuclear bombs built by South Africa are examples of gun-type devices. Gun assembly is relatively simple; the Little Boy and South African devices were produced without the benefit of a nuclear test. Gun assembly is inefficient, however, and too slow to permit the use of plutonium. (Unlike HEU, plutonium's high rate of spontaneous neutron emission guarantees that the chain reaction would start and fizzle out before a sufficiently supercritical mass could be assembled.)

Most nuclear weapons use implosion, which is much more efficient than gun assembly. The sphere or shell of NEM at the center of an implosion device, usually clad with beryllium or another metal, is called the "pit." Either plutonium or HEU (or both) may be used, but plutonium is preferred because the mass of NEM required—and therefore the size of the resulting nuclear weapon—is smaller.

The yield of an implosion device can be increased or "boosted" by introducing a mixture of tritium and deuterium gas into the hollow pit. The tritium and deuterium undergo fusion at the high densities and temperatures created by the implosion, producing high-energy neutrons that significantly enhance the fission chain reaction. The "boost gas" typically is stored in an external reservoir and transferred through a tube into the pit just before the weapon is detonated. Because tritium decays with a half-life of 12 years, reservoirs must be replaced on a regular schedule.

In a thermonuclear or two-stage weapon, the implosion device is called the "primary." Thermal radiation from the detonation of the primary is used to compress a physically separate "secondary." The secondary assembly contains both fusion fuel and in most cases uranium (some or all of which may be HEU); this package, as it is delivered to the weapon assembly facility, is called a "canned subassembly" (CSA) in the United States. Compression of the secondary creates fusion reactions, releasing neutrons that fission the uranium. The secondary is responsible for most of the energy released by a strategic weapon, which is why the primary is sometimes called a "trigger."

The primary and secondary are housed inside a radiation case; the completed assembly is called the "physics package." A deliverable nuclear weapon is produced by integrating the physics package with the safing, arming, fuzing, and firing system; neutron generators; batteries; and other components inside a bomb case or reentry vehicle.

* Radiological dispersion devices use conventional explosives to disperse radioactive material. Even though they may contain NEM, they cannot produce a nuclear explosion and thus do not satisfy our definition of a nuclear weapon.

BOX 2-2

Encrypted Messages and Message Digests

In secure declarations, each record or line (which, in the case of itemized declarations, might describe the location and characteristics of a particular weapon) can be thought of as sealed in an opaque numbered envelope that cannot be opened without the key to that particular envelope. Opening the envelope by force or stealth is not possible. The declaring party hands a stack of these sealed envelopes to the receiving party. Some time later, according to agreed rules, the receiving party can request the keys that will allow selected envelopes to be opened, to permit the accuracy of the records contained within to be confirmed.

The exchange of encrypted declarations as sketched in the text makes use of AES encryption, in which each plain-text line (PL) is encrypted using a publicly known, standard encryption algorithm and a separate, secret key for each PL. The keys can be generated randomly using various techniques, at the option of the declaring party. The encrypted line thus produced by the declaring party is the "cipher line" (CL), which would be transmitted to the receiving party. The declaring party would retain a copy of each PL and the key used for that PL. Disclosure of a particular PL could be achieved by transmitting the corresponding secret key so that the receiving party could decrypt the CL using the same algorithm in decipher mode. Alternatively, the declaring party could supply the PL along with the corresponding key and the receiving party could apply the encryption algorithm to confirm that the previously transmitted CL resulted.

Encryption involves protecting new secrets—the encryption keys—in addition to the original information in the declaration, but the keys can be protected at least as well as the original information. No method has yet been found that can break encrypted messages much faster than an exhaustive key search. Thus, if the keys are 128 bits in length, the receiving party would on average have to try 2^{127} keys to find the correct one to decrypt a given CL, or over 10^{42} tries to decrypt all of a declaration consisting of 10,000 CLs. This should be computationally infeasible for another 70 years, even if computer speeds continue to double every 18 months, as they have over the last 20 years.* For an extra margin of safety, longer keys can be used; for example, the use of 256 bit keys would increase the required number of tries to over 10^{80}—about one try for every nucleon in the universe.

Another approach is to exchange "message digests" rather than encrypted messages. This is called a "commitment," because the message digest commits the declaring party to supply a particular message. Cryptographic hash functions are widely used to prepare message digests; for example, the U.S. government-approved Secure Hash Algorithm SHA-1 is used to prepare a 160 bit message digest (MD) from the individual plain-text line PL. SHA-1 is fully disclosed and no deficiency has been noted by the large international community interested in such matters.

A brief analysis illustrates that it is impossible to determine or guess the PL (and the warhead data it contains) from its MD. Assume that the 160 bit MD produced by SHA-1 depends on the value and the position of each character in the PL, that the PL includes a nonce field (a string of random characters) of at least 1,024 bits, and that the PL itself is 2,048 bits total. There are 2^{2048} possible PLs and only 2^{160} possible MDs; thus, each MD corresponds on average to $2^{2048}/2^{160} = 2^{1888} \cong 10^{568}$ possible instances of PL. The given set of nuclear weapon data might have been combined with any of $2^{1024} \cong 10^{308}$ instances of the nonce field, producing 10^{308} possible PLs. Thus, any of the weapon data lines could be used to produce the same MD when paired with very many instances of the nonce field. Therefore, it is fundamentally impossible, even with infinite computing capability, to deduce the original weapon data from the MD.

Hash functions are also designed to have "collision resistance" and "preimage resistance." Collision resistance means that it is computationally infeasible to find two PLs that produce the same MD. This is important, because otherwise the declaring party could commit to two different sets of data for each weapon, and produce whichever value was less damaging at the time. Preimage resistance means that it is computationally infeasible to find a PL that produces a particular MD. This is important, because otherwise the declaring party could find a nonce field which, when combined with *any* given set of nuclear weapon data (e.g., chosen to match the results of an inspection), would produce the previously exchanged MD, rendering the commitment meaningless.

As with encryption, computational infeasibility is a quantitative question rather than a fundamental one, and an extra margin of safety can be obtained by using digests with a larger number of bits. With SHA-1, the declaring party would have to try 2^{160} trial hashes to find a preimage and 2^{80} trials to find a collision. The recently approved SHA-256, which produces 256 bit digests, would provide preimaging resistance equivalent to symmetric encryption with 256 bit keys, and collision resistance equivalent to a key size of 128 bits. Additional security could be provided by concatenating the outputs of two or three different hash functions, to guard against the possible future discovery of a collision-finding algorithm for one of the chosen hash functions.

*Arjen K. Lenstra and Eric R. Verheul, "Selecting Cryptographic Key Sizes," *Journal of Cryptology* 14 (4) (2001), pp. 255-293.

BOX 2-3

Tags and Seals

A tag is any intrinsic characteristic or applied feature that uniquely and unambiguously identifies a particular item, such as a nuclear weapon or weapon canister. The simplest tag is the serial number or bar code that may already be stamped into or attached to the item. For verification purposes, it may be preferable to use an intrinsic or applied feature that is more difficult to duplicate, remove, or alter without detection.

A seal is a tamper-indicating device that prevents undetected access. A seal need not prevent access (e.g., to the contents of a weapon canister); it need only record in some permanent and unambiguous manner that such access has occurred. The absence of a seal is one such unambiguous record.

Tags and seals are usually used together; for example, a weapon canister may be tagged and the canister sealed so as to prevent the undetected removal of the weapon inside or the transfer of the tag. The tag and seal can be integrated into the same device; for example, a clamped bundle of optical fibers passed through a hasp can be used both as a unique identifier and as a seal. The distinctive pattern produced when light is transmitted through the bundle of fibers is extremely difficult to reproduce, serving as both a unique identifier and a tamper-revealing seal.

The advantage of using tags and seals for verification is that they can provide unambiguous evidence of a violation, even if inspections occur infrequently or if only a small sample of the items are inspected. Discovery of a single weapon without a valid tag or a single canister with a broken seal would be *prima facie* evidence of a violation. A party wishing to cheat could not introduce weapons or canisters without valid tags and seals into declared facilities without running substantial risk of detection.

Many types of tags and seals have been developed for commercial as well as arms control and nonproliferation purposes, ranging from bar codes and tamper-indicating tape to electronic tags and seals. Tags and seals are used routinely by the International Atomic Energy Agency to safeguard civilian nuclear materials and by the U.N. Monitoring, Verification and Inspection Commission (previously the UN Special Commission on Iraq) to track items that could be used for both civilian and military purposes. Several types of tags and seals were developed for use with the INF and START I treaties and, more recently, for use in nuclear weapon and NEM transparency applications.

An "intrinsic" tag or seal takes advantage of unique microscopic features of each item, such as the surface of a metal container or a weld joining the lid and the container. Techniques have been developed to record and compare these microscopic features using plastic castings, scanning electron microscopy, and microvideography. Techniques also have been developed to record and compare the unique acoustic signatures generated when an item is interrogated by sound waves of various frequencies.

A "passive" tag or seal is an applied feature, such as a serial number or bar code, that works without electrical power. Examples include various types of fiber optic tags and seals, reflective particle tags (reflective particles dispersed in an applied acrylic film), shrink-wrap (plastic film that is wrapped around items, creating a distinctive pattern), and wire loop seals.

An "active" tag or seal, which requires a power supply, can continuously monitor its status and record indications of tampering; some can be interrogated remotely and report their identity and status. These include electronic and radio frequency tags and seals, active fiber optic seals, and smart bolts. Several devices can be integrated into a single tag/seal, including video cameras; motion, temperature, and tamper sensors; memory devices; and radio frequency transmitters.

Before selecting a particular tag and seal technology it would be important to carefully think through the procedures for their application, validation, and removal, and to do a complete vulnerability assessment of the potential for counterfeiting, spoofing, and undetected tampering or removal. The challenge is to select technologies and procedures that make counterfeiting and spoofing by the inspected party much more difficult, time consuming, and costly than detection by the inspecting party of such counterfeiting or spoofing. The best choice may be an inexpensive tag or seal that is readily validated in the field, with a small sample collected by the inspecting party for detailed laboratory analysis. Even the simplest devices can be designed with features that are extremely difficult to counterfeit.

Vulnerability analysis also must consider the possibility that a tag or seal could hinder the proper operation of an item or could collect intelligence information. Such concerns could be overcome through joint design and manufacture, together with random selection of tags and seals produced by the other party for detailed laboratory examination.

BOX 2-4

Identifying Nuclear Weapons and Weapon Components: Templates, Attributes, and Information Barriers

Some types of treaty-limited objects are easily and accurately identified; for example, photographic observation—even from a satellite—has been considered sufficient to determine that a ballistic missile or a submarine is authentic. It is similarly easy to determine that other objects are not missiles or submarines. It is not so straightforward, however, to correctly identify a nuclear weapon: to ensure that an object that is declared to be a nuclear weapon really is a nuclear weapon, or that an object that is declared not be a nuclear weapon really is not one.

Two general approaches to this problem have been developed: the "template" approach and the "attribute" approach. These are described in more detail in Boxes 2-4A and 2-4B. Templates identify a nuclear weapon or weapon component by matching certain of its characteristics to the characteristics of a weapon or component that is known or believed to be authentic. Attributes identify weapons and components by requiring that they display a certain set of characteristics possessed by all weapons or components. U.S. and Russian nuclear weapon laboratories have done considerable collaborative work to develop both approaches for arms control purposes and have produced several prototype systems to identify both nuclear weapons and weapon components.*

Both approaches require measuring an agreed set of characteristics. Most of the template and attribute systems that have been developed use measurements of the radiation (gamma rays and neutrons) emitted during the natural radioactive decay of plutonium and uranium isotopes. These measurements can be used to characterize the composition, mass, shape, and arrangement of these and surrounding materials and thereby can be used to identify an object as a nuclear weapon or weapon component with various degrees of confidence.

Each approach has strengths and weaknesses. Attributes identify objects with a single set of measurements; in the template approach, such measurements are compared with those for one or more reference objects. Templates therefore require the storage of information, while attributes do not. Attributes require specifying a set of characteristics that are true of all nuclear weapons or weapon components; templates do not. Templates can identify particular types of nuclear weapons or weapon components; attributes cannot. In general, templates can be far more difficult to spoof than attributes, assuming that the reference objects are authentic.

The attribute approach alone is unlikely to work well for nuclear weapons, due to the difficulty of specifying a set of attributes that would be displayed by all authentic weapons but not by any nonweapon objects. The attribute approach is particularly vulnerable to scenarios in which the inspected party creates a number of low-cost dummy weapons that display the selected set of attributes, which could be substituted for genuine weapons. The inspecting party might believe that the genuine weapons had been retired or dismantled, when only the dummy weapons had been dismantled and the genuine weapons were stored in a secret facility.

Templates are better suited to the problem of identifying weapons. The primary disadvantages are the need to create a template for each weapon type, to have confidence that the reference object is an authentic weapon, and the need to securely store templates between inspections. The template approach could be vulnerable to scenarios in which a fake weapon is presented for templating, or in which the signatures of genuine weapons are modified or disguised so that they do not match any template.

If parties wish to have high confidence that nuclear weapons are genuine and that other objects are not weapons, it probably will be necessary to combine the template and attribute approaches. Data gathered for a template, for example, could be analyzed to determine whether the object contains certain general characteristics or attributes of an authentic nuclear weapon, such as the presence of a certain minimum amount of weapon-grade plutonium metal and high explosive.

In either approach, measurements performed for identification purposes may contain sensitive information about the design of the nuclear weapon or component; this is particularly true for gamma-ray measurements. For this reason, template and attribute identification systems are likely to require an "information barrier" to protect the measurement, storage, and analysis of sensitive data. Only the result of the analysis (e.g., "yes" or "no") would be transmitted to the inspecting party. Information barriers are described in more detail in Box 2-4C.

Before implementing an actual system employing templates or attributes, a critical review should be undertaken to confirm the extent of the real security concerns involved in order to avoid unnecessary complication in the equipment and procedures required.

* U.S. Department of Energy, Office of Nonproliferation Research and Engineering, "Technology R&D for Arms Control," NNSA/NN/ACNT-SP01 (Livermore, CA: Arms Control and Nonproliferation Technologies, Spring 2001).

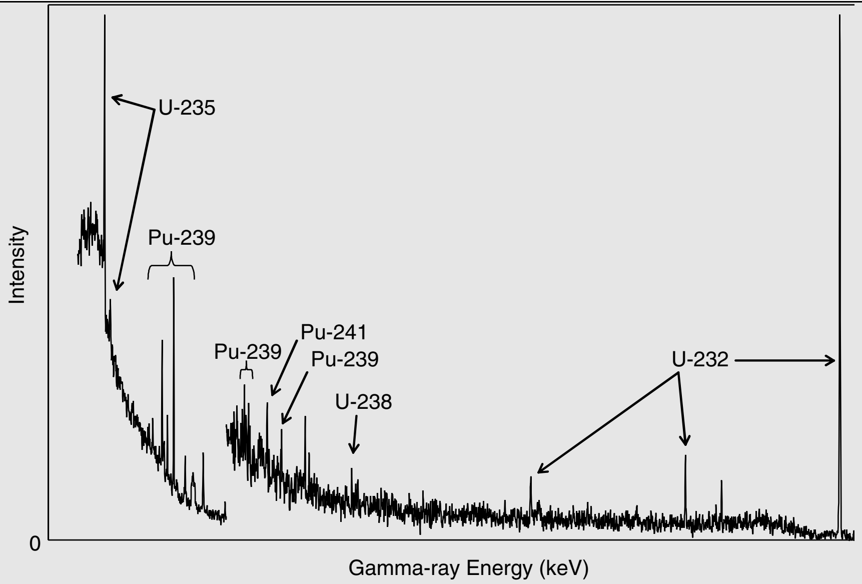
BOX 2-4A

Template Identification

The template approach works by measuring certain characteristics of an object and comparing them with the same set of measurements taken from a reference object (e.g., an authentic weapon of a particular type): the template. If the two sets of measurements match, one can conclude that the object is a weapon of that type. The set of characteristics included in the template could include various combinations of a weapon's mechanical, thermal, electrical, acoustical, and nuclear properties, but most concepts have relied entirely on gamma-ray emissions. Template systems based on gamma-ray spectra have been used for decades by the United States and Russia to identify their own weapons and weapon components; in Russia these gamma-ray templates are called "radiation passports."

The key components of nuclear weapons contain NEM, which are radioactive. Most of these isotopes emit gamma rays at a particular set of energies, and the isotope can be positively identified by its gamma-ray spectrum. These gamma rays are scattered and absorbed as they pass through materials inside the weapon; the fraction scattered or absorbed depends on the composition and thickness of the material and the energy of the gamma ray. Some isotopes also emit neutrons that, when absorbed by certain materials, result in the emission of gamma rays at particular energies. These many interactions result in a spectrum of gamma rays of various energies and intensities outside the weapon.

An example of such a gamma-ray spectrum, recorded with a high-resolution detector, is shown below. More than two dozen peaks can be identified at energies corresponding to the decay of particular plutonium and uranium isotopes or neutron interactions with particular materials. The intensity of the various peaks depends on the exact composition, geometry, and configuration of many weapon materials and components. Weapons and weapon components of different types produce distinguishably different spectra.



Illustrative gamma-ray spectrum of a Soviet nuclear weapon.

Adapted from: Steve Fetter et al., *Science* 248 (May 18, 1990), pp. 828-834.

Using the template approach for inspections presents several challenges. The most fundamental challenge is establishing the authenticity of the template—that the template was produced using an authentic weapon or weapon component. If the inspecting party is allowed to select, from the complete list of declared weapons or components, one or a few of a particular type for the template, one could be fairly confident that the selected weapon or component is authentic. In the case of nuclear weapons, this is particularly true if the chosen weapon is operationally deployed. A less satisfactory but simpler procedure would have the inspected party present several weapons or components of a given type to inspectors, who would then choose one for the template. Either scheme could be subverted by manufacturing and substituting bogus devices in place of weapons of a given type (with the authentic weapons moved to secret facilities). Although this seems unlikely, one could protect against this scenario to some extent by using the attribute approach to ensure that the objects presented for templating meet certain criteria expected of all weapons.

Another challenge is protecting the sensitive weapon design information that may be contained in the template. According to present security criteria, gamma-ray spectra would have to be protected at all times: when templates are produced, stored, and when they are used to identify objects during inspections. Sensitive data can be protected during template measurement and analysis using an information barrier (see Box 2-4C).

Protecting templates between measurements is a special challenge. Templates most likely would be stored on a removable disk or computer chip. The disk or chip must be protected so that the inspected party could not alter the data without detection and the inspecting party could not access the data. This could be done by placing the disk in a safe that requires two combinations to open, one held by each side; additional protection could be provided by encrypting the data with a two-part cryptographic key, with one part held by each side. Alternatively, the inspected party could have sole possession of the template and the information barrier could provide the inspecting party with a digest or “secure hash” of the template when it is made and each time it is subsequently used (see Box 2-2). This digest would uniquely identify the template and unambiguously confirm its authenticity, but the inspected party could not derive any information about the template from the digest.

The U.S. Department of Energy has sponsored the development of several template-measuring and information barrier systems. These have demonstrated that a system could be designed for monitoring purposes that would reliably identify weapons while preventing the release of sensitive information. Brookhaven National Laboratory developed the Controlled Intrusiveness Verification Technology (CIVET) system, which was demonstrated to Russian scientists in 1997. Sandia National Laboratories modified CIVET for use with the Radiation Identification System to produce the Trusted Radiation Identification System (TRIS). Tests conducted at the Pantex plant demonstrated that TRIS could reliably identify various types of weapons and weapon components (pits and canned subassemblies).

A sample of the TRIS results for templates representing five weapon types appears in the table below. For each template/object combination, the table gives a statistic that measures the goodness of fit between the object’s spectrum and the template. If the object is the same type as that used for the template, the value of the statistic should be about one; a value below a threshold of two or three might be used to indicate a match, with a very low probability of a false negative. In tests the system correctly indicated a match every time the object was the same type of weapon used to make the template, and correctly indicated no match in all other cases. Similar results were also obtained when identifying pits and canned subassemblies (CSAs), with one exception: the template system could not distinguish between components with very similar designs. This is not a problem in an arms control context, in which there is no need to distinguish between items that are almost identical.

Active systems. Template systems based on intrinsic gamma-ray emissions—sometimes called “passive” systems—should work well for U.S. weapons, since they contain plutonium and uranium isotopes that emit penetrating gamma rays that are readily detectable and cannot easily be shielded. The penetrating gamma rays emitted by U.S. HEU are due to very small concentrations of uranium-232—an isotope that does not exist in nature but that is produced in nuclear reactors. U.S. HEU is contaminated with this isotope because uranium recovered from spent nuclear fuel was used to produce enriched uranium. It is believed that HEU in Russia and the other nuclear weapon states is similarly contaminated. It is possible, however, that weapons that contain uncontaminated weapon-grade HEU exist or might be assembled in the future. Because the low-energy gamma rays emitted by uranium-235 are readily absorbed by other weapon materials or easily shielded, the gamma-ray emissions from such weapons may be too weak to provide a useful template, if they do not include plutonium as well.

	Template for Weapon Type				
Object	**A**	**B**	**C**	**D**	**E**
Weapon Type A, #1	0.8*	92	32	7.7	42
Weapon Type A, #2	0.9	90	31	8.2	45
Weapon Type A, #3	0.8	91	32	8.5	45
Weapon Type B	496	0.8	140	336	491
Weapon Type C	63	43	0.9	34	128
Weapon Type D	11	102	26	0.6	46
Weapon Type E	55	174	86	31	1.0
Pit, Type A	558	91	319	547	794
Pit, Type E	858	203	566	821	1071
CSA, Type A	52	118	88	64	66
CSA, Type E	27	156	77	22	6.4

[*] The “reduced chi-square” is a measure of the goodness-of-fit between the object’s spectrum and the template. The gamma-ray spectrum between 80 and 2,750 keV was divided into 16 groups (two of which are discarded) and the number of counts in each group for the object and the template was computed; the reduced chi-square is the sum over all groups of the squared difference in the number of counts for the object and

template divided by the variance, divided by the number of degrees of freedom.

Adapted from: D.J. Mitchell and K.M. Tolk, "Trusted Radiation Attribute Demonstration System," *Proceedings of the 41st Annual Meeting of the Institute of Nuclear Materials Management* (Northbrook, IL: Institute of Nuclear Materials Management, 2000).

To deal with such problems and provide a more robust template, an external radiation source could be used to stimulate fission in the weapon's plutonium and uranium components. An example of an "active" system is the Nuclear Material Identification System (NMIS) developed by Oak Ridge National Laboratory, which uses an external neutron source and time coincidence and correlation techniques to accurately characterize fissionable materials using the neutrons and gamma rays emitted during fission events. The external neutron source required is modest, with an emission rate only several times greater than that of a plutonium pit. In a blind experiment, NMIS correctly distinguished between 16 different types of weapons and components, demonstrating its usefulness for template identification. An information barrier would be needed, as the data would contain information about the mass and geometry of the nuclear components. The need for an external neutron source and the greater complexity of the required hardware and software, which would complicate authentication, makes it unlikely that such systems would be used for monitoring purposes unless templates based on intrinsic gamma-ray emissions were judged not to provide the required degree of confidence.

Unclassified Templates. There may be several nonradiation types of measurements that could be used as templates to identify nuclear weapons. Templates that do not contain sensitive weapon design information would be useful, because they would eliminate the need for information barriers and would greatly simplify template storage and the certification and authentication of the measurement system. It may be possible, for example, to distinguish weapon types based on a combination of their acoustic, electromagnetic, and/or thermal signatures. Such alternatives have not received as much attention as radiation templates, probably because they are seen as easier to spoof.

BOX 2-4B

Attribute Identification

The attribute approach works by measuring a set of characteristics or "attributes" that should be displayed by all items of a given general type. To satisfy a given attribute, measurements of a weapon or component would have to fall above an agreed threshold or within an agreed range of values.

This approach works best for items with the same general composition and design; for example, all plutonium pits contain a certain minimum amount of weapon-grade plutonium metal in a symmetrical shape. The United States developed a prototype attribute system to confirm the authenticity of plutonium pits to be stored in a U.S.-funded facility at Mayak, Russia. This system used six attributes:

1. The presence of plutonium;
2. Weapon-grade plutonium (Pu-240:Pu-239 < 0.1) ;
3. Plutonium age (separated prior to January 1,1997);
4. Plutonium mass (> 0.5 kilogram);
5. Symmetry of plutonium mass; and
6. Absence of plutonium oxide (< 10 percent plutonium oxide).

The first three attributes were measured with high-resolution gamma-ray spectrometry; for example, the ratio of the intensities of the 642.5 keV and 646.0 keV gamma rays emitted by Pu-240 and Pu-239, respectively, is directly proportional to the Pu-240:Pu-239 ratio. Similarly, the relative intensities of gamma rays emitted by the Am-241 decay products of 14-year half-life Pu-241 can be used to determine its age (the time elapsed since the plutonium was last chemically purified). Plutonium mass was estimated using the number of single, double, and triple neutron events from Pu-240 spontaneous fission recorded by a neutron multiplicity counter, together with the Pu-240:Pu-239 ratio determined by gamma-ray spectrometry. Plutonium symmetry was determined with a neutron multiplicity counter, by requiring that the number of counts in each of eight detectors was within 15 percent of the combined average. The absence of plutonium oxide (a surrogate for the presence of plutonium metal) was measured using data from both detectors.

As with templates, an information barrier must be used to protect the sensitive information contained in these radiation measurements (see Box 2-4C). In the system described above, the detectors and computers were housed inside shielded enclosures, all data were stored in volatile memory, and a "security watchdog" monitored the system for unauthorized access. The only output was a set of green or red lights to indicate whether the item being inspected satisfied each of the six attributes.

This prototype system was demonstrated to a team of Russian scientists in the Fissile Material Transparency Technology Demonstration held at Los Alamos National Laboratory in August 2000. Although the system was developed to confirm the authenticity of pits, Russia now plans to store excess weapons plutonium in unclassified shapes at the Mayak facility.

The attribute approach could be extended to other NEM components. Because HEU emits few high-energy gamma rays and almost no neutrons, passive radiation measurements are able to do little more than indicate the mere presence of HEU. As with templates, an "active" system would be necessary to provide a reasonable set of attributes for components that contain only HEU; for example, the Nuclear Material Identification System (NMIS) described in Box 2-4A could be used with a low-intensity neutron source to determine the mass and enrichment of HEU components.

Applying the attribute approach to weapons is less straightforward because it is difficult to specify a single set of attributes that would be displayed by all possible types of nuclear weapons. Different classes of weapon may require different sets of attributes. For weapons that contain a plutonium pit, one might select attributes that indicate the presence of a certain amount of weapon-grade plutonium in a symmetrical shape surrounded by high explosive. The presence of high explosive could be indicated by the gamma rays that are emitted when neutrons are absorbed by nitrogen in the high explosive. As noted in the text, the attribute approach may be best applied to nuclear weapons as a complement to templates, to provide further confidence that items are genuine.

A key difference between the attribute and template approach is that attributes cannot be used to identify the particular type of nuclear weapon or component. Whether this is an advantage or disadvantage depends on the nature of the transparency regime and whether parties wish to exchange and confirm declarations that include such details.

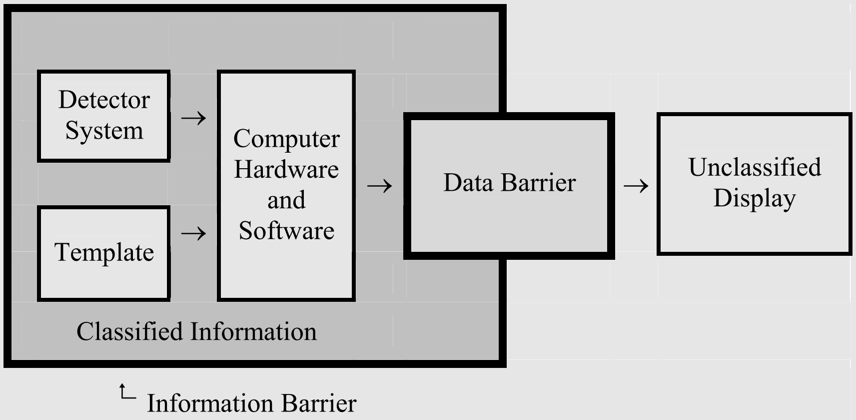
A key advantage of the attribute approach over the template approach is that identification is based solely on measurements of the item under inspection and there is no need to store sensitive data for later comparisons. On the other hand, the specification of each attribute must be known to all parties, which could touch on sensitive information, such as the minimum amount of plutonium in a pit. This requirement, together with the need to accommodate differences among the various types of weapons and components and the desire to prevent false negatives (i.e., an authentic weapon or component that fails to display a particular attribute due to measurement error), could lead to thresholds for attributes that are well below the average values for most weapons. The threshold for plutonium mass selected by the United States was set at 0.5 kilograms, for example, which is believed to be well below the average. These factors make the potential for false positives (i.e., a nonweapon object that displays the set of attributes for a weapon) a greater concern for the attribute approach.

BOX 2-4C

Information Barriers

A key challenge in implementing a template or attribute system is protecting any sensitive weapon design information that may be gathered during the identification process. This can be accomplished by automating the collection, storage, and analysis of data, and by making only the conclusions of the analysis available to the inspectors; for example, a computer could light a green lamp if an object's gamma-ray spectrum matched the template or an attribute within specified tolerances, or it might report a summary statistic that measures the degree to which the object's spectrum and the template matched.

As illustrated in the figure below, the detector, computer, and template storage are housed inside an "information barrier" which prevents transmission of electronic signals or other surreptitious access to the sensitive data contained inside. Countries could build the systems used to inspect their own weapons, so they could be sure there were no hidden transmitters or storage devices or intentional flaws in the information barrier.



Because an information barrier prevents access to the data and the analysis upon which the results of an inspection are based, the inspecting party must authenticate the system. The inspecting party must be confident that the results produced by the system accurately describe inspected objects over the full range of possible objects and conditions, and that the system contains no hidden features that could interfere with or bypass the proper analysis or result (e.g., hardware or software changes that produce a green light during every inspection, or that allow the system to respond to remote commands from the inspected party).

Authentication can be facilitated by cooperative design of measurement and information barrier systems; thorough documentation; the use of simple, commercially available hardware; and the documentation of all source code for system software. If these guidelines are followed, the system can be authenticated by thoroughly examining the hardware and software and confirming that they correspond to the documented design. The inspected party could build multiple identical units and allow the inspecting party to choose one for weapon inspections and another for detailed examination, including the removal of selected components for laboratory testing. After a system is authenticated, tamper-revealing seals can be placed in key locations to detect any attempt to alter the system. Proper operation of the system over a range of conditions can be checked using a variety of unclassified test objects, which could be provided by either party.

As noted in Boxes 2-4A and 2-4B, prototype information barrier systems have been developed by the United States for template and attribute measurement systems, and their use was demonstrated to Russian scientists during the Fissile Material Transparency Technology Demonstration.

3

Nuclear-Explosive Materials

Chapter 2 examined the possibilities for applying monitoring and transparency measures to all categories of nuclear weapons and to their nuclear-explosive components. This chapter considers the further challenges of transparency and monitoring for military and civilian stocks of nuclear-explosive materials (NEM). These materials are readily convertible by nuclear weapon states—or other states or groups that have knowledge of nuclear weapons technology—into the nuclear-explosive components of actual weapons. And the size of the NEM stocks determines, to a reasonable approximation, how many weapons of particular types could be made. Moreover, the difficulty of producing such materials means that their acquisition is and will remain a limiting factor for states or sub-national groups aspiring to make such weapons.

Meaningful constraints on stocks of NEM require knowing how much NEM is possessed by whom and being able to monitor additions and subtractions. Achieving such constraints and the ability to monitor them is important not only for building confidence among nuclear weapon states about the current and potential future sizes of the arsenals of the other nuclear weapon states, but also for building international confidence in the durability of reductions in those arsenals and for limiting and monitoring the risks of proliferation of nuclear weapons to additional actors.

The importance of NEM stocks resides not just in their role in determining the breakout potential from agreed or unilaterally undertaken limits on the nuclear arsenals of the existing global and regional nuclear weapon states, but also in their role as a reservoir of proliferation potential to both other state and nonstate actors. Stocks of NEM held by non-nuclear weapon states confer the potential for these states to acquire nuclear weapons of the simplest types quite quickly once a decision to do so has been made. Moreover, all such NEM stocks represent nuclear weapon production potential for any state or nonstate actor that is able to steal these materials or to buy or otherwise acquire them from their legitimate or illegitimate possessors.

This chapter begins with an introduction to the characteristics of NEM, the means by which these materials are produced, and current stocks and flows of NEM in the military and civilian sectors. (This treatment is supplemented with more detail in Appendix A) The chapter then addresses the challenges of transparency and monitoring for NEM, first in conceptual terms and then in terms of the specific bilateral and multilateral measures that have been undertaken up until now in connection with cooperative efforts to account for, secure, and protect both military and civilian materials[1]

DEFINITION, CHARACTERISTICS, AND PRODUCTION OF NEM

All nuclear weapons rely on the energy released by an explosively growing fission chain reaction—a process in which heavy nuclei split into lighter ones following absorption of free neutrons and, in splitting, release more neutrons that in turn induce more fissions, and so on. Only a few nuclides[2] of the hundreds that exist are capable of sustaining the explosive nuclear chain reaction needed for a nuclear weapon. Such nuclear-explosive nuclides include U-235, U-233, and all the isotopes of plutonium, among others. A nuclear-explosive material is one in which the proportions of nuclear-explosive nuclides and nonexplosive nuclides of the same elements are such as to permit an explosive chain reaction if the material is present in suitable quantity, density, chemical form and purity, and configuration.

In the simplest nuclear weapons, the fission chain reaction is the only source of the nuclear energy that is released. In more advanced nuclear weapons, such as "boosted" fission weapons and thermonuclear weapons, some of the energy is generated by fusion reactions that are ignited by energy from the fission explosion.

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[1] The arguments in this chapter build on those in National Academy of Sciences, Committee on International Security and Arms Control, *Management and Disposition of Excess Weapon Plutonium*, 2 vols. (Washington, DC: National Academy Press, 1994 and 1995); Steve Fetter, *Verifying Nuclear Disarmament*, Occasional Paper 29, Henry L. Stimson Center, Washington, DC, 1996; and Independent Bilateral Scientific Commission on Plutonium Disposition, *Final Report,* Washington, DC: President's Committee of Advisors on Science and Technology, The White House, and Russian Academy of Sciences, June 1997.

[2] "Nuclide" is the general term for a species of atom as characterized by both its atomic number (equal to the number of protons in the nucleus, which determines the element to which a nuclide belongs) and its mass number (equal to the number of protons and neutrons combined, which determines which isotope of the element it is). See Appendix A.

(Fusion reactions merge light nuclides, most notably isotopes of hydrogen, to form heavier ones, accompanied by a large release of energy.) In boosted fission weapons, the energy directly added by the fusion reactions is very modest, but the high-energy neutrons emitted by these reactions lead to a large increase in the amount of fission that takes place; in thermonuclear weapons a significant fraction of the energy released comes from fusion reactions.

Countries aspiring to make boosted and thermonuclear weapons, however, cannot do so without first mastering simpler pure-fission weapons. Terrorists working without the support of a state would not be able to make the much more demanding boosted and thermonuclear weapons at all. Thus it is mastery of the explosive fission chain reaction—including possession of the quantities of NEM needed to achieve one—that governs who can make nuclear weapons.

Types of NEM

The most widely used definitions of the isotopic mixtures and concentrations constituting NEM are as follows: [3]

- Any mixture of uranium-235 (U-235) with the more abundant, non-nuclear-explosive isotope U-238 in which the U-235 concentration is 20 percent or more is considered NEM. This form of NEM is referred to as highly enriched uranium (HEU).[4]
- Any mixture of U-233 with U-238 when the U-233 concentration is 12 percent or more is considered NEM.[5]

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[3] See IAEA, *IAEA Safeguards Glossary,* 2001 Edition (Vienna: International Atomic Energy Agency, 2002). Available as of January 2005, at: http://www-pub.iaea.org/MTCD/publications/PDF/nvs-3-cd/PDF/NVS3_prn.pdf and Nuclear Energy Research Advisory Committee (NERAC), *Attributes of Proliferation Resistance for Civilian Nuclear Power Systems* (Washington, DC: U.S. Department of Energy, October 2000).

[4] Nuclear explosives can in principle be made with material containing somewhat less than 20 percent U-235, but the amount of material required at enrichments below 20 percent is very large.

[5] At this percentage, the mass of material required for criticality is similar to that for a mixture of U-238 and U-235 containing 20 percent U-235. See, for example, C. W. Forsberg, C. M. Hopper, J. L. Richter and H. C. Vantine, *Definition of Weapons-Usable Uranium-233*, ORNL/TM-13517 (Oak Ridge, TN: Oak Ridge National Laboratory, March 1998).

- Any mixture of plutonium isotopes in which the concentration of plutonium-238 (Pu-238) is *less* than 80 percent is considered NEM.[6]

These materials are considered NEM irrespective of whether the uranium or plutonium are present in metallic form or as oxides, or nitrates, or fluorides, or some other compound. This is because, even if a particular uranium or plutonium compound will not itself support a nuclear explosion (and some will), transforming such compounds chemically into the metal is a straightforward operation that would be within the reach of any group with a modicum of competence in chemistry.

Mixtures of NEM with other elements, in compounds or otherwise, can differ greatly in the difficulty of separating out the NEM in a purity that would permit an explosion, however. In particular, the intense radiation field emitted by typical spent nuclear fuel from civil power reactors presents great technical difficulties (and hazards) in the separation of the contained NEM (a mix of plutonium isotopes amounting altogether to 1-2 percent of the mass of the spent fuel) from the accompanying fission products and low enriched uranium. Accordingly, the NEM in spent fuel is considered to be a smaller proliferation hazard than NEM in most other forms, and in international practice is subject to less stringent monitoring and security measures.

Fortunately, NEM does not exist in nature in any significant quantity, and all types of NEM are quite difficult to produce, creating an important constraint on access to nuclear weapons capabilities.

- U-235, for example, constitutes only about 0.7 percent of naturally occurring uranium; achieving the higher U-235 concentration needed for a nuclear weapon (or for most types of nuclear reactors) requires "uranium-enrichment" technology that is difficult to master and costly, as discussed further below.
- The isotopes of plutonium (most importantly Pu-239, but also Pu-238, Pu-240, Pu-241, and Pu-242) are practically nonexistent in nature; they can be obtained in

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[6] The IAEA defines all plutonium isotopes containing less than 80 percent Pu-238 as "direct-use material," a phrase with a meaning similar to our "nuclear-explosive material." The IAEA's exclusion of high-purity Pu-238 appears to have been intended to avoid complications in the use of such material for power generators on peaceful space-based and remote unmanned applications. It is also true that the higher the concentration of Pu-238 in plutonium, the greater the difficulties posed for weapon design by this isotope's high rate of heat generation.

quantity only by bombarding naturally occurring "fertile" materials with neutrons in an accelerator or a reactor, then separating the plutonium from accompanying elements (also discussed further below).

- U-233 is likewise essentially nonexistent in nature and producible in quantity only in a reactor or accelerator; relatively little U-233 appears to have been produced for weapon purposes to date, nor has this isotope been produced in significant quantities in civilian nuclear energy operations (although its use as the fissile component in a "thorium fuel cycle" has been much analyzed and discussed).

More obscure nuclides that could sustain an explosive nuclear chain reaction include neptunium-237 and several isotopes of americium, curium, and californium. These have been less important than plutonium, U-235, and U-233 because they have existed until now in much smaller amounts and because producing them in quantity is even more difficult.[7]

The fuels that generate energy from fusion in boosted and thermonuclear weapons—notably tritium, deuterium, and lithium—might also be argued to be nuclear explosives. But no means is yet known for releasing explosive nuclear energy from these fusion fuels alone, so their possession without the material required for an explosive fission chain reaction does not enable the manufacture of nuclear weapons. It is possible that the importance of tritium in advanced weapon design might nonetheless make it a focus for limits and monitoring similar to those for NEM in a more comprehensive nuclear arms limitation and transparency regime, but we do not treat the problem of accomplishing this in this report.[8]

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[7] A case can be made, however, that attention does need to be given to monitoring and protecting the growing stocks of at least some of these nuclides, most notably Np-237 and Am-241. See David Albright and Lauren Barbour, "Troubles Tomorrow? Separated Neptunium 237 and Americium," in David Albright and Kevin O'Neill, eds., *The Challenges of Fissile Material Control* (Washington, DC: Institute for Science and International Security, 1999).

[8] But see Martin B. Kalinowski and Lars C. Colschen, "International Control of Tritium to Prevent Horizontal Proliferation and to Foster Nuclear Disarmament," *Science and Global Security* 5 (1995), pp. 131-230. Available as of January 2005, at: http://www.princeton.edu/%7Eglobsec/publications/pdf/5_2kalinowski.pdf, which treats the benefits, challenges, and possibilities of international controls and verification for tritium in considerable detail.

Key Characteristics of NEM

HEU can be used to make a nuclear weapon using either the relatively simple "gun type" design concept or the more complicated "implosion" design concept: plutonium isotopes, irrespective of the mixture, will work only in weapons of the implosion type.[9] In either case, however, nuclear weapon design is easiest—and the mass of NEM involved is smallest—when the nuclear material is not just barely NEM but is "weapon grade." This is generally taken to be greater than 90 percent U-235 in HEU and greater than 90 percent Pu-239 in plutonium.

Because the bare critical mass of weapon-grade HEU is about 60 kilograms, a hypothetical gun-type weapon could be made with this amount of material, while an implosion weapon could be made from considerably less of the same material. The International Atomic Energy Agency (IAEA) defines a "Significant Quantity" (SQ) relevant to construction of a nuclear weapon to be 25 kilograms of U-235 in HEU; the SQ value for plutonium is set at 8 kilograms, as is the SQ for U-233 (which like U-235 will work in either gun-type or implosion designs).[10]

Considerably less knowledge and manufacturing skill are needed to make a gun-type weapon than to make an implosion weapon, and a gun-type design is more likely to work without nuclear testing than an implosion weapon. In addition, because of the relative ease of handling HEU compared with plutonium, HEU is even a greater threat than plutonium as the potential object of theft for use by terrorists or proliferant nations with limited access to nuclear weapon expertise.

Pathways to Obtain NEM

The principal pathways exploited to date for the production of NEM have been (a) mining of uranium ore, followed by enrichment of the concentration of U-235 to nuclear-explosive levels,

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[9] These and many other aspects of the science and technology of NEM are elaborated in Appendix A.

[10] The IAEA definition of SQ reads: "the approximate amount of nuclear material for which the possibility of manufacturing a nuclear explosive device cannot be excluded. Significant quantities take into account unavoidable losses due to conversion and manufacturing processes and should not be confused with critical masses." See International Atomic Energy Agency, *IAEA Safeguards Glossary: 2001 Edition* (Vienna: International Atomic Energy Agency, 2002), p. 23, as well as Appendix A.

and (b) creation of plutonium by absorption of neutrons in U-238 in a reactor, followed by chemical separation of the plutonium from the accompanying fission products and uranium. The two approaches are described briefly here; additional detail is provided in Appendix A.

Uranium-235

Natural uranium, as mined, contains 0.72 percent of the nuclear-explosive nuclide U-235 and 99.27 percent U-238, which is not a nuclear explosive. (About 0.006 percent is U-234, which is also not a nuclear explosive.) Enrichment of the U-235 concentration to nuclear-explosive levels, that is, to 20 percent U-235 or more, is a sufficient technological challenge to have constituted one of the principal technical barriers to the spread of nuclear weapons capability over the past 60 years.

The currently practical processes for enriching the concentration of U-235 exploit the 1.3 percent difference in mass between U-235 and U-238 atoms. The uranium is first converted to uranium hexafluoride gas (UF_6), which can then be processed to achieve a degree of separation of the slightly lighter uranium hexafluoride gas molecules containing U-235 from the slightly heavier uranium hexafluoride molecules containing U-238. The two most widely used means of doing this have been (a) *gaseous diffusion plants*, which exploit the difference in the diffusion rates of the lighter and heavier molecules through a "cascade" of thousands of porous barriers, and (b) *centrifuge plants*, which use stages of hundreds or thousands of sophisticated, ultra-high-speed, gas centrifuge machines to separate the molecules based on their differing inertial masses.

The gaseous diffusion and centrifuge plants currently in use around the world in connection with civilian nuclear power generation are operated to enrich uranium only to a U-235 concentration of 3 to 5 percent, which cannot produce a nuclear explosion. In terms of the "enrichment work" needed to separate isotopes, these concentrations are more than half way toward the 90+ percent enrichment levels desirable for nuclear weapons. In principle, commercial enrichment plants could be operated in a manner to do the remaining work needed to bring this low enriched reactor fuel up to weapon-usable levels.

Separated Plutonium

Plutonium-239 is produced when U-238 absorbs neutrons produced in a reactor or by an accelerator. Consequently, Pu-239 is produced automatically in any nuclear reactor containing U-238 in its fuel. The Pu-239 itself then absorbs neutrons to produce higher isotopes of plutonium in quantities depending on the irradiation time. (See Table 3-1 for the isotopic composition of various grades of plutonium.)

TABLE 3-1 Compositions of Various Grades of Plutonium

Grade	Pu-238	Pu-239	Pu-240	Pu-241	Pu-242
Super-grade	---	0.98	0.02	---	---
Weapon-grade	0.00012	0.938	0.058	0.0035	0.00022
Reactor-grade	0.013	0.603	0.243	0.091	0.050
MOX-grade	0.019	0.404	0.321	0.178	0.078
FBR blanket	---	0.96	0.04	---	---

Pu-241 includes its Am-241 daughter. Reactor grade Pu is from 33 MWd/kg HM LEU fuel stored 10 years before reprocessing. MOX grade is from 33 MWd/kg HM 3.64 percent fissile Pu MOX stored 10 years before reprocessing.

Adapted from: J. Carson Mark, "Explosive Properties of Reactor Grade Plutonium," *Science and Global Security* 4 (1993), pp. 111-128. See Appendix A for elaboration of the relevant definitions and parameters.

The plutonium produced in this way is, by the nature of the process, intimately mixed with fission products, as well as with uranium-238 that has not absorbed neutrons. In this form the plutonium cannot be used to make a nuclear weapon but must first be separated from the fission products and the U-238. This can be accomplished by chemical means, since Pu-239 and other isotopes of plutonium form distinct chemical compounds. The term "separated plutonium," is used when the concentrations of accompanying fission products and uranium are reduced to levels such that the material, if present in sufficient quantity, would support a nuclear explosion.

Figure 3-1 shows in schematic form the production, utilization, and disposition pathways for HEU and plutonium in the nuclear weapon and nuclear energy complexes.

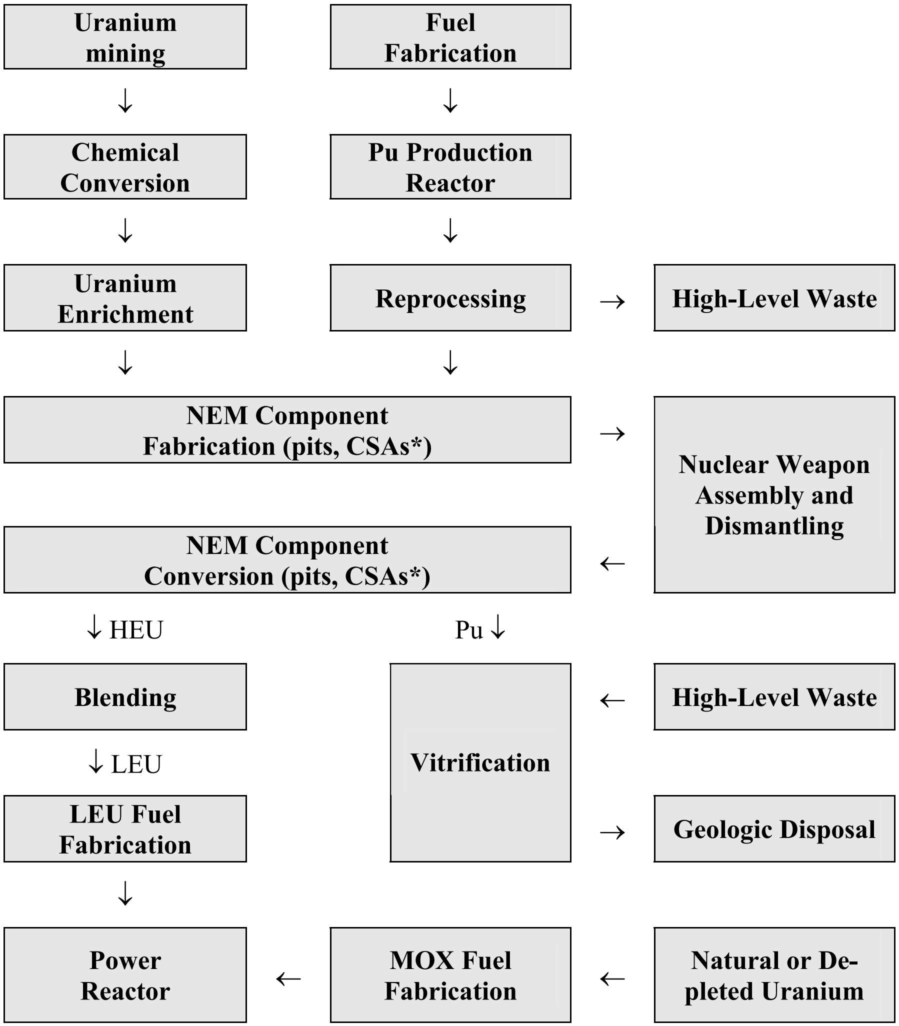

FIGURE 3-1 Production, utilization, and disposition flows for HEU and plutonium.
*CSAs = Canned Subassemblies.

STOCKS AND FLOWS OF NEM IN THE MILITARY AND CIVIL SECTORS

The quantity, character, and geographic distribution of stocks and flows of military and civil NEM worldwide are important dimensions of the challenge of achieving transparency and monitoring for these materials.[11] More detail on these stocks and flows is provided in Appendix A.

World Military and Civilian NEM Stockpiles

The United States and Russia hold the largest stockpiles of NEM, but only limited information about them is available publicly. The United States keeps a computerized national plutonium and HEU inventory, including both Department of Energy (DOE) and nongovernment stockpiles, known as the Nuclear Materials Management and Safeguards System (NMMSS).[12] What has been released publicly from this database up until now includes principally detailed data on U.S. warhead dismantlement rates; a detailed production history for U.S. plutonium, plus data on the stockpiles of this material; and official information on total U.S. production of HEU (but not the detailed production history or information on the current stockpile). Official information on the size, locations, and characteristics of Russia's stockpiles of warheads and NEM remains classified at this writing.

Estimates of global stocks of plutonium and HEU as of the end of 2003, compiled from publicly available information by the Institute for Science and International Security, are shown in Table 3-2. The totals are approximately 1,900 metric tons each of plutonium and HEU,[13] amounting to more than 200,000 SQ of the former and about 75,000 SQ of the latter.

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[11] The most extensive unclassified compendium of such information is David Albright, Frans Berkhout, and William Walker, *Plutonium and Highly Enriched Uranium 1996: World Inventories, Capabilities, and Policies* (New York: Stockholm International Peace Research Institute and Oxford University Press, 1997). Albright and colleagues periodically post updates to this work at the Web site of the Institute for Science and International Security available as of January 2005, at: http://www.isis-online.org.

[12] See the NMMSS Web site, available as of January 2005, at: http://www.nmmss.com/.

[13] A metric ton is 1000 kilograms or 2204.6 pounds. The HEU estimates are expressed as "weapon-grade uranium equivalent," in which inventories at a range of enrichment values above 20 percent have been converted, based on U-235 content, to equivalent tons of uranium enriched to 93 percent U-235.

The HEU of military origin is mainly in intact weapons; in weapon components, ingots, oxides, and scrap; in naval fuel; and in fuel for military plutonium production and tritium production reactors. In the United States, as of the end of 2003, about 125 tons of HEU of military origin that had been declared excess to military needs was under civil control, prior to being blended down to low enriched uranium (LEU) for use in power reactors. In Russia, about 300 tons of HEU of military origin that had similarly been declared excess to military needs was likely still in military custody. The few tens of tons of HEU of civil origin, which are mainly in research reactors and the fresh or spent fuel for these, are not much compared with the major power military stockpiles, but at circa 2,000 SQ they represent a serious risk in terms of possible use in weapons by proliferant states or terrorist groups.

TABLE 3-2 ISIS Estimates of Global Inventories of Plutonium and HEU (Metric tons, end of 2003, rounded)

Material	Military Origin	Civil Origin	Total
HEU	**1840**	**60**	**1900**
Pu	**260**	**1595**	**1855**
of which irradiated	--	1365	1365
of which unirradiated	260	230	490

As indicated in Table 3-2, about 500 tons of the world's plutonium is in unirradiated form (often referred to as "separated" form, meaning that it has been separated from the intensely radioactive fission products that accompany it in irradiated nuclear fuel). This unirradiated or separated material requires at most straightforward chemical processing (for example, to convert it from plutonium nitrate or plutonium oxide to plutonium metal) before it can be used in a weapon. The 230 tons of this material of civil origin amounts by itself to something like 80,000 Significant Quantities. The further 1,400 tons of irradiated plutonium—mostly in the cores or spent fuel from power reactors—is considered to be a smaller proliferation hazard because of the need for technically demanding reprocessing to extract the plutonium in weapon-usable form. The actual difficulty and danger of that reprocessing operation vary considerably, however, with the degree of irradiation experienced by the fuel and the time that has passed since irradiation.

Adapted from: David Albright and Kimberly Kramer, "Fissile Material Stockpiles Still Growing," *Bulletin of the Atomic Scientists*, (November/December 2004), pp 14-16. See also the underlying analysis on the Web Site of the Institute for Science and International Security, available as of January 2005, at: http://www.isis-online.org.

Of the world's military stockpiles of HEU and plutonium, the United States and Russia possess more than 95 percent. The remainder is possessed by the United Kingdom, France, China, India, Pakistan, Israel, and North Korea. Civilian plutonium in power reactor fuel exists in all of the dozens of countries where power reactors exist. Separated civilian plutonium exists in significant quantities in several of the nuclear weapon states as well as in Germany, Japan, Belgium, and Switzerland. At least kilogram quantities of civilian HEU for research reactors exist at approximately 135 operating HEU-fueled research reactors in more than 40 countries, ranging from the United States to Ghana.[14] Most of these research reactors have only small amounts of HEU—but some, including a significant number outside the nuclear weapon states, have enough fresh HEU for a bomb. Even more have enough HEU for a bomb if irradiate fuel that is not radioactive enough to deter suicidal terrorists from taking it and using it in a bomb is taken into account.[15]

Flows of NEM

All of the five *de jure* nuclear weapon states have indicated they are not reprocessing plutonium or producing HEU for weapons. India, Pakistan, Israel, and North Korea continue production that is small on the scale of global stockpiles, but significant in the context of their modest existing stocks.

Overall, the global stockpile of HEU is declining by more than 30 tons each year, as only modest production continues; 30 tons are blended to LEU in the U.S.-Russian HEU purchase agreement every year; some U.S. excess HEU is blended each year; and additional amounts of HEU are consumed as fuel in research reactors, nuclear-powered naval vessels, nuclear-powered icebreakers, and the like.[16] Numerous shipments of large quantities of HEU over thousands of kilometers take place in Russia every year (and to a much lesser extent in the United States), as HEU components are shipped from weapons dismantlement sites and HEU is processed and blended to LEU. International shipments of HEU, almost en-

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[14] Matthew Bunn and Anthony Wier, *Securing the Bomb: An Agenda for Action* (Washington, DC: Nuclear Threat Initiative and the Project on Managing the Atom, Harvard University, May 2004), pp. 58-59, and references cited therein. Available as of January 2005, at: http://www.nti.org/e_research/analysis_cnwmupdate_052404.pdf.

[15] See Edwin Lyman and Alan Kuperman, "A Re-Evaluation of Physical Protection Standards for Irradiated HEU Fuel" (paper presented at the 24th International Meeting on Reduced Enrichment for Research and Test Reactors, Bariloche, Argentina, November 5, 2002). It should be noted, however, that fresh or spent research reactor fuel could not be used to make a nuclear explosive until the uranium was separated from the aluminum or other inert matrix, since the small density of the uranium in the fuel greatly increases the critical mass.

[16] In many cases, the spent fuel from these systems remains HEU, but the total amount of HEU (in tons of 93 percent U-235 equivalent) is reduced as U-235 is fissioned.

tirely as fuel for research reactors or targets for medical isotope production reactors, have declined to a low level since the 1992 Schumer Amendment placed strict limits on U.S. HEU exports.

Stocks of both separated and unseparated plutonium, by contrast, are increasing every year, and international flows are substantial. The operation of the world's civilian power reactors leads to the discharge of about 80 tons per year of plutonium embedded in 8,000 tons of spent nuclear fuel.[17] In recent years, roughly 20 tons of this material has been separated by reprocessing each year, and the rate of fabrication of separated plutonium into mixed oxide fuel for actual loading into power reactors has been about one half that amount, leading to a growing stockpile of civilian separated plutonium that will soon surpass the amount of separated plutonium in all the world's military stockpiles combined.[18] (In addition, roughly 1.2 tons of separated plutonium is reprocessed from the spent fuel of Russia's three remaining military plutonium production reactors each year, which continue to operate because they provide essential heat and power to nearby communities, and whose fuel was not designed for long-term storage.[19]) Since the plutonium inventory in spent nuclear fuel has been growing at about 60 tons per year, the total plutonium inventory in spent plus active nuclear fuel has been growing at about 70 tons per year.

Large quantities of plutonium in spent fuel are routinely shipped to reprocessing plants, and large quantities of weapon-usable separated plutonium are shipped from reprocessing plants to fuel fabrication plants and, in the form of fabricated mixed oxide (MOX) fuel, from fabrication plants to reactor sites, each year. Such shipments of separated plutonium take place on a large scale

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[17] Unless otherwise noted, estimates in this discussion of plutonium flows are from David Albright, Frans Berkhout, and William Walker, *Plutonium and Highly Enriched Uranium 1996: World Inventories, Capabilities, and Policies* (New York: Stockholm International Peace Research Institute and Oxford University Press, 1997) and updates posted on the Web site of the Institute for Science and International Security, available as of January 2005, at: http://www.isis-online.org.

[18] For a recent tabulation of data on civilian plutonium stockpiles declared to the IAEA, see Matthew Bunn, "Unclassified Estimates of Russia's Plutonium and HEU Stockpiles—And World Civilian Plutonium Stockpiles: A Summary and Update," Revision 1, Managing the Atom Project, Belfer Center for Science and International Affairs, John F. Kennedy School of Government, Harvard University, July 23, 2003 (unpublished).

[19] For a discussion, see U.S. Congress, General Accounting Office, *Nuclear Proliferation: DOE's Effort to Close Russia's Plutonium Production Reactors Faces Challenges, and Final Shutdown is Uncertain,* GAO-04-662 (Washington, DC: Government Accountability Office, June 2004). Available as of January 2005, at: http://www.gao.gov/new.items/d04662.pdf.

within France (which has the world's most active plutonium recycling program), and on a more modest scale to and from Belgium (which has a modest-size MOX fabrication plant), and from France and the United Kingdom to customers in Germany, Japan, and elsewhere. Limited shipment of military plutonium from weapon dismantlement sites to storage sites presumably takes place, but all plutonium components from dismantled weapons in the United States, and most in Russia, are believed to be stored at the weapon dismantlement sites.

NEM TRANSPARENCY AND MONITORING: GENERAL ISSUES

In principle, transparency and monitoring arrangements for NEM could be analogous to the case of warheads discussed in Chapter 2; they could consist of making declarations of the stocks possessed at a given time, cooperating in the measures needed for others to confirm that the declarations are correct, and allowing and facilitating the monitoring of the stocks from that time forward (including the monitoring of additions and subtractions). The approaches and tools available for implementing these practices in the case of stocks of NEM are substantially similar to those treated in Chapter 2 for the case of intact weapons and components, notably:

- providing comprehensive declarations of the locations, quantities, types, and physical, chemical, and isotopic forms of all NEM stocks;
- allowing inspections of declared NEM facilities and sites to confirm and clarify the declarations;
- maintaining and making available, for inspection and analysis, records of the locations, characteristics, and operating histories of facilities capable of producing, modifying, or destroying NEM;
- applying and interrogating tags and seals on containers and storage rooms for NEM;
- installing and operating monitored perimeter-portal systems that exploit radiation and other distinctive signatures to confirm that what enters and leaves any given facility is what it is supposed to be;
- equipping storage, production, and processing areas with appropriate sensors and accountability systems to monitor declared activity and detect undeclared activity related to NEM at those sites, the recordings from

which can either be examined during periodic inspections or uploaded via the Internet or satellites for transmission to a monitoring center; and
- allowing for on-site inspections of both declared and suspect sites in the event of detection of suspicious activity or unexplained discrepancies.

As in the case of nuclear weapons, such "cooperative transparency" for NEM could be supplemented by information gathered unilaterally by individual states (through National Technical Means, information obtained by clandestine operations, and information obtained from defectors and whistle blowers).

Comparing the Transparency Challenges of NEM and Nuclear Weapons

The rest of this chapter emphasizes aspects of transparency and monitoring for NEM that differ from what has already been presented in relation to intact weapons and their components in Chapter 2. Such differences are related, among other issues, to accounting uncertainties, secrecy issues, physical evidence of production, and the existing system of monitoring of civilian NEM in non-nuclear weapon states by the IAEA.

Accounting Uncertainties

In the case of intact nuclear weapons and their nuclear-explosive components, the numbers are at least precisely known by the countries that possess them. Their inventories are confined to a relatively limited number of sites (at least in peacetime), and both the incentives and the capabilities of the countries that own them to rigorously keep track of them are high. By contrast, NEM occur in a much wider variety of applications and locations (civil as well as military) than nuclear weapons. Many of the forms in which NEM exist also are not "item countable" but rather are bulk commodities that are inherently more difficult to keep track of. Indeed, NEM accounting even by those with unrestricted access to the relevant facilities is plagued by measurement uncertainties, including both those resulting from the inherent limits of available measuring equipment and those from the "holdup" of material in inaccessible locations in the facilities that produce and process these materials.[20]

In the United States, for example, when the U.S. government prepared a detailed inventory of its plutonium holdings through 1994, including a comparison of the current inventories at its facilities with the records of production and use of plutonium, it reported total cumulative "inventory differences"—that is, unexplained differences between input to various facilities and the sum of output and present inventory—of 2.8 tons of plutonium, 2.5 percent of the 111.4 tons produced or acquired.[21] (In addition, 3.4 tons of plutonium was estimated to have been lost to waste, though the uncertainties in assessing the specific amounts of plutonium in such wastes are large.) There is no evidence that any of this material was stolen (though that possibility cannot be entirely excluded). Rather, these inventory differences are generally the result of inaccurate measurement (particularly during the first decades of the nuclear age, when measurement technology was in its infancy and the premium was on production to support the arms competition, rather than accountancy), holdup of material within facilities (such as material plated onto the interior surfaces of pipes), and possibly overestimation of how much material was produced in the first place. Nevertheless, clearly such irreducible uncertainties, amounting to enough material for hundreds of nuclear weapons in the case of the United States and Russia, will have to be taken into

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[20] See, for example, U.S. Department of Energy, Deputy Assistant Secretary for Security Evaluations, *Increasing Fissile Inventory Assurance Within the U.S. Department of Energy* (Washington, DC: Department of Energy, January 1995). This study concluded that "an accurate inventory is necessary for continued assurance against theft or diversion," and that inventories accurate enough to meet that goal or to "fully support international activities" such as permitting inspection of DOE sites were not yet in place – in part because "most of the holdup at DOE facilities has not been accurately measured, and some has not been measured at all," and because some 10 tons of plutonium and 100 tons of HEU existed in scrap and other forms that were difficult to measure accurately. In response, DOE established a Fissile Material Assurance Working Group, which made a wide range of recommendations for improving accounting practices at DOE, many of which have since been implemented. (See Thomas P. Grumbly, memorandum to Victor H. Reis, Alvin L. Alm, Martha A. Krebs, and Terry R. Lash, "Fissile Material Assurance Working Group Recommendations," February 11, 1997). The difficulties of achieving accurate measurements of material in waste, holdup, and scrap remain substantial.

[21] U.S. Department of Energy, *Plutonium: The First 50 Years: United States Plutonium Production, Acquisition, and Utilization From 1944 Through 1994* (Washington, DC: Department of Energy, February 1996). Available as of January 2005, at: http://www.osti.gov/html/osti/opennet/document/pu50yrs/pu50y.html. Another useful treatment of this and related points is Steve Fetter, *Verifying Nuclear Disarmament*, Occasional Paper 29, Henry L. Stimson Center, Washington, DC, 1996.

account in considering how accurate and effective any potential regime of declarations and the monitoring of these could be.

Practices that render material accounting programs ineffective as a means of confirming that enough material for a bomb has not been removed continue to be uncovered at U.S. sites, and similar practices presumably take place at sites in other states as well.[22] Russia has not yet prepared an inventory comparable with the published U.S. plutonium inventory, though U.S. and Russian experts have discussed such an effort.[23] Discussions with Russian experts concerning accountancy practices in the former Soviet Union suggest that the uncertainties there will be even higher, and the complications in matching current inventories to production histories even greater.[24]

Bookkeeping for HEU is also difficult, in part because the U-235 concentration varies so widely in both enriched material and in the depleted "tails" from enrichment. (Freshly enriched uranium can vary from 1 percent U-235 in very low enriched fuel for cer-

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[22] For the U.S. case, see Martha C. Williams and Dewey L. Whaley, "Observed Practices That Can Adversely Affect an MC&A Program," in *Proceedings of the 44th Annual Meeting of the Institute of Nuclear Materials Management, Phoenix, Arizona, July 14-17, 2003* (Northbrook, IL: Institute of Nuclear Materials Management, 2003). Williams and Whaley report, for example, cases where holdup in process was not measured but defined as the difference between input and output—a practice that makes it impossible to detect whether the difference is actually caused by unauthorized removal of material. For a case in a non-nuclear weapon state subject to IAEA safeguards, it is instructive to consider the case of Japan's Tokai reprocessing plant, where IAEA estimates and Japanese estimates of material began to diverge as soon as the facility began operating in the 1970s, and it was not until decades later, after the difference had increased to some 200 kilograms of plutonium, that improved approaches to measuring the plutonium being sent to waste, which were then retroactively applied to estimate the amount of plutonium sent to waste over the facility's lifetime, were finally agreed and implemented, bringing Japanese and IAEA estimates into line. See, for example, International Atomic Energy Agency, "New Measurement Techniques Correct Pu Inventory in Japanese Reprocessing Plant," PR/2003/02, January 28, 2003.

[23] Gennadi M. Pshakin et al., "Russian-American Cooperation in Developing a Russian Plutonium Registry," in *Proceedings of the 43rd Annual Meeting of the Institute of Nuclear Materials Management* (Northbrook, IL: Institute of Nuclear Materials Management, 2002).

[24] Russia does not yet have a complete national computerized inventory of its stockpiles, only a combination of computer-based and paper records. Many Russian facilities have not had the resources to perform complete measured inventories of their nuclear material holdings in recent years, and most Russian experts expect that such inventories would reveal substantial differences from paper records on the inventories. The chief engineer for one of Russia's major plutonium production facilities, for example, reported that until U.S.-Russian cooperation began, the very concept of inventory differences or material unaccounted for did not exist at his facility: the difference between input and output was *defined* as losses to waste. Matthew Bunn, "The Threat in Russia and the Newly Independent States," 2004. Available as of January 2005, at:
http://www.nti.org/e_research/cnwm/threat/russia.asp.

tain reactors up to 80-98 percent U-235 in HEU for use in weapons and some naval propulsion reactors. Depleted uranium typically contains 0.2-0.4 percent U-235, but sometimes is outside these bounds.) The bookkeeping problem is further complicated by the possibilities for recycling of uranium in a number of ways; for example, natural uranium might be irradiated in the reactor to produce plutonium, followed by use of the residual uranium recovered at the reprocessing plant as input to a uranium enrichment plant making HEU. In addition, uranium of specific U-235 concentrations needed for particular applications can be and has been produced by blending HEU with depleted uranium, natural uranium, or LEU. Record keeping of the quantities and concentrations of the input and output flows from such operations was not always complete, and the gaps make it very difficult to reconcile existing inventories exactly with records of past production, use, and reuse.

As with plutonium, moreover, significant amounts of uranium with varying degrees of enrichment are held up in the equipment and piping of enrichment and processing facilities (such as weapon component or fuel fabrication facilities); this is particularly the case for gaseous diffusion enrichment plants. In addition, in the United States at least, the quantities of HEU in scrap and other difficult-to-measure forms are far larger than the comparable quantities of plutonium. A U.S. declaration on its HEU production was completed in the late 1990s and declassified in 2001, but has not been made public. The unexplained inventory differences in that inventory are presumably substantial, and it should be expected that when Russia prepares a comparable inventory, the uncertainties will be even larger (though Russia long ago transitioned from gaseous diffusion to centrifuges for its enrichment operations, and centrifuge enrichment involves lower irreducible accounting uncertainties, because of the much lower quantity of in-process uranium at any given time).[25]

The military plutonium and HEU stockpiles that exist in other states are dramatically smaller than those in the United States and Russia. The stockpiles in Britain, France, and China each amount to a few percent of the U.S. or Russian stockpiles and the stockpiles in India, Pakistan, Israel, and North Korea each amount to far

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[25] For a discussion of the history of HEU production and use in the United States, Russia, and other nuclear weapon states, based on the limited unclassified information available, see David Albright, Frans Berkhout, and William Walker, *Plutonium and Highly Enriched Uranium 1996: World Inventories, Capabilities, and Policies* (New York: Stockholm International Peace Research Institute and Oxford University Press, 1997).

less than 1 percent of the U.S. or Russian stockpiles. Thus the total magnitude of the accounting uncertainties for NEM in these cases should be expected to be dramatically smaller than that in the U.S. and Russian cases, even if the uncertainties are the same or worse in terms of the percentage of the total quantity of NEM produced.

Civilian plutonium and HEU stockpiles in non-nuclear weapon states are already monitored by the IAEA (see below). Here, too, accounting uncertainties pose significant issues, at least for those types of facilities where NEM is bulk processed in large quantities (such as plutonium reprocessing plants, or facilities that fabricate fuels containing plutonium or HEU). International standards have been developed for the expected accuracy of material measurement in different processes, and are regularly updated.[26] Currently, the standard deviation of safeguards measurements at a large reprocessing plant are expected to be in the range of 1 percent of throughput and the uncertainties at a centrifuge enrichment plant only in the range of 0.2 percent of throughput (no large gaseous diffusion enrichment plants are under IAEA safeguards at present). But the uncertainties at a waste store are expected to be in the range of 20 percent of the stored material.[27]

Secrecy Issues

A difference that makes transparency for NEM easier to implement than transparency for weapons is that the characteristics of many forms of NEM are less sensitive and accordingly less highly classified than the characteristics of actual weapons. While nuclear weapons are unambiguously military,[28] large quantities of NEM

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[26] For the most recent update for particular kinds of measurements, see H. Aigner et al, "International Target Values 2000 for Measurement Uncertainties in Safeguarding Nuclear Materials," *Journal of Nuclear Materials Management* 30 (Winter 2002). Available as of January 2005, at: http://www.inmm.org/topics/contents/JNMMPaperITV.pdf.

[27] See the presentations in International Atomic Energy Agency, *International Course on Agency Safeguards 44,* Vienna, Austria, October-December 2000.

[28] Non-weapon uses of nuclear explosives for major construction projects, stimulation of natural gas deposits, and the like were explored experimentally by the United States and the Soviet Union in the 1960s and 1970s and also attracted some interest subsequently in China. Potential applications of nuclear explosives for space propulsion and for defending the earth from wayward comets and asteroids have been proposed but never pursued beyond the conceptual stage. None of these possibilities is currently attracting much attention: U.S. and Russian experiments with "Peaceful Nuclear Explosives" (PNEs) showed little promise of economic and environmentally acceptable use. Although the Chinese initially proposed language to permit monitored tests for peaceful purposes during the negotiations for the Comprehensive Nuclear Test Ban Treaty (CTBT), it was generally recognized that this would greatly weaken the treaty, perhaps fatally, since it would provide a convenient cover for weapon development. In return for China's withdrawal of its proposal, a provision was incorporated

were produced and are being used for civilian purposes, and the characteristics of these are not classified. (Information on specific locations where enough material for a bomb exists may be sensitive, however, particularly if these locations are not well secured.)

The secrecy situation with respect to military NEM is more complex. The United States has declassified and published detailed information on its plutonium inventory and past production, and information on at least its total production of HEU; the United Kingdom has also declassified detailed information on its plutonium production and current inventory, and its current HEU inventory. But Russia and other states with military NEM stockpiles continue to regard both the size of their current inventories and the production histories of these inventories as secret information. Similarly, while the United States now regards most of the general characteristics of weapons plutonium as unclassified, Russia still counts both the isotopic and chemical composition of weapons plutonium as secrets,[29] and it is likely that other nuclear weapon states currently have similar policies. The specific isotopic compositions of HEU used for military purposes are classified in both the United States and elsewhere, as are the chemical and physical forms of HEU used as naval fuel, the amounts of such fuel used each year, and the amounts of such material present at particular locations.

In short, substantial quantities of NEM around the world are not classified, and thus pose fewer monitoring challenges than warheads do, but there are also substantial quantities of NEM that are not in assembled nuclear weapons or weapon components but that are nonetheless subject to very significant secrecy constraints.

Physical Evidence of Production

Another important difference between transparency and monitoring for warheads and for NEM is that production of NEM, in some cases, leaves behind physical evidence that can be compared

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in Article VIII that at a review conference 10 years after the treaty entered into force any party could request consideration of the possibility of conducting tests for peaceful purposes. If the Conference decided by consensus (without objection) that such tests would be permitted, an appropriate treaty amendment would be submitted to a special amendment conference (Article VIII), which could adopt the amendment by a majority vote provided no state vetoed the action. In short, a double veto essentially precluded a future amendment permitting tests for peaceful purposes.

[29] Hence in the U.S.-Russian Plutonium Management and Disposition Agreement of 2000, provisions are included allowing each side to blend the weapons plutonium subject to disposition with a limited amount of civilian plutonium, preventing the other side from learning the detailed composition of the original weapons plutonium.

with declarations of past production, to check that the evidence is consistent with the declarations. In the case of nuclear warheads, production records for warhead assembly and disassembly plants can be exchanged, as discussed in Chapter 2, but there is nothing about the physical state of these plants that would help confirm the number of nuclear weapons that had been assembled or disassembled there. In the case of plutonium, the moderator or structural materials in plutonium production reactors absorb neutrons as irradiation of nuclear material to produce plutonium proceeds. In a process known as "nuclear archaeology," these structural materials can be examined to estimate how much plutonium was produced in that reactor, and this evidence can be compared with declarations and other information.

Similar physical evidence of total production is not available for uranium enrichment, but examinations of depleted uranium from enrichment operations can provide some information on how much material was processed when, with what levels of U-235 in the waste. When such information is combined from declarations and other sources, it can help to build confidence that a declaration of production is accurate, or highlight discrepancies that suggest it may not be. These subjects are addressed in more detail in Chapter 4.

IAEA Monitoring of Civilian NEM Stocks in Non-Nuclear Weapons States

The differences described above between intact warheads and NEM have negative and positive implications for transparency and monitoring. The negative aspect of this difference is that monitoring of NEM is more difficult, given the size and dispersal of the stocks and flows and facilities associated with the nonweapon uses of these materials, than it would be if NEM were confined to the nuclear weapon sector. The positive aspect is that the civil-military "dual use" character of NEM makes monitoring of some NEM much less sensitive. As a result, the world community has been able to establish under the Nuclear Non-Proliferation Treaty (NPT) of 1970 a system under which all civilian NEM in non-nuclear-weapon state parties to that treaty are declared to, and inspected by the IAEA—as are all facilities in those states capable of producing NEM—under detailed terms negotiated between the agency and the individual states. All states except India, Israel, Pakistan, and with its recent withdrawal, North Korea, are parties to the NPT. Similarly, civilian NEM within the EURATOM states of the European Union are under EURATOM safeguards, even if the states concerned are nuclear weapon states (Britain and France).[30] Thus, the only NEM stockpiles not generally already subject to monitoring even more intrusive than most of the measures assessed in this report are military NEM stockpiles, and the civilian NEM stockpiles of nuclear-weapon states other than Britain and France.[31]

As discussed further below, the IAEA safeguards system has provided invaluable experience with procedures and technologies for monitoring civil nuclear materials stocks and facilities while respecting the sensitivities of the possessor countries, but at the same time has demonstrated the limitations of existing procedures. The system, which has been under more or less constant expansion and improvement since its establishment in 1970, provides an extensive experience base for measures to monitor NEM, and could be extended to cover civil NEM in nuclear weapon states, and at least the portion of military NEM stocks that these states deem surplus to their military needs.

TRANSPARENCY AND MONITORING FOR NEM: HISTORY, STATUS, AND THE ROAD AHEAD

The main efforts to date on developing elements of transparency and monitoring for military NEM have occurred in the context of U.S.-Russian relations since the end of the Cold War.[32] Some multilateral efforts in this domain have also taken place, most importantly under the auspices of the IAEA. Transparency and monitoring for civil NEM, on the other hand, have been driven largely by the international safeguards responsibilities and practices of the IAEA pursuant to the NPT. In this section we augment

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[30] Like the IAEA, EURATOM relies on material accounting supplemented with containment and surveillance for its safeguards system, though the specific standards, approaches, and purposes of the EURATOM system are somewhat different. See Commission of the European Communities, "Operation of Euratom Safeguards in 2002" (Brussels: European Commission, 2003). Available as of January 2005, at: http://europa.eu.int/comm/energy/nuclear/safeguards/doc/com_2003_0764_en.pdf.

[31] Some of the civilian material in nuclear-weapon states or in non-parties to the NPT *is* under IAEA safeguards, under voluntary agreements between the weapon states and the Agency, or at the insistence of countries that supplied particular facilities or materials. A Chinese enrichment plant supplied by Russia, for example, is under Agency safeguards, and an Indian reprocessing plant has safeguards during those periods when it is processing nuclear material provided by the United States or other suppliers that insist on such safeguards.

[32] A number of U.S.-Russian efforts at transparency for NEM from dismantled nuclear weapons were already mentioned in Chapter 2 in connection with the discussion there of the post-Cold War U.S.-Russian nuclear-weapons initiatives.

the discussion in Chapter 2 of U.S.-Russian initiatives relating to military NEM, then turn to the multilateral dimension of efforts toward transparency and monitoring for this material, and finally treat the IAEA-centered efforts relating to civilian NEM. Under each of these headings, there is a brief review of the recent history, current status, and relevant transparency issues, together with consideration of options to improve these capabilities.

U.S.-Russian Transparency and Monitoring Efforts for Military NEM

The treatment in Chapter 2 of the linked transparency initiatives for nuclear weapons and military NEM is augmented in this section under six subheadings: transparency for NEM from dismantled weapons; exchange and confirmation of declarations on total stocks of NEM; transparency at Nunn-Lugar sites; monitoring issues in plutonium production and disposition; unilateral openness initiatives and informal cooperation; and lab-to-lab cooperation on transparency technologies, followed by a concluding discussion of considerations and options looking ahead.[33]

Transparency for NEM from Dismantled Weapons

Even prior to the September 1994 Clinton-Yeltsin summit agreement mentioned in Chapter 2, U.S. Secretary of Energy Hazel O'Leary and Russian Minister of Atomic Energy Victor Mikhailov agreed to establish a regime of mutual inspections to confirm the inventories of plutonium and HEU removed from dismantled nuclear weapons. This initiative eventually came to be called, somewhat redundantly, "Mutual Reciprocal Inspections" (MRI). In 1994 and 1995 U.S. and Russian experts carried out a number of joint experiments and came close to agreeing on the specific types of measurements that would be used to confirm that an inspected canister contained a plutonium weapon component; a less intrusive

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[33] Key sources for additional detail on each of these topics are Matthew Bunn, Anthony Wier, and John P. Holdren, *Controlling Nuclear Warheads and Materials: A Report Card and Action Plan* (Washington, DC: Nuclear Threat Initiative and the Project on Managing the Atom, Harvard University, March 2003) and the companion Nuclear Threat Initiative Web site available as of January 2005, at: http://www.nti.org/cnwm. See also James Goodby, "Transparency and Irreversibility in Nuclear Warhead Dismantlement," in Harold A. Feiveson, ed., *The Nuclear Turning Point: A Blueprint for Deep Cuts and De-Alerting of Nuclear Weapons* (Washington, DC: The Brookings Institution, 1999), and Oleg Bukharin and Kenneth Luongo, *U.S.-Russian Warhead Dismantlement Transparency: The Status, Problems, and Proposals*, PU/CEES Report No. 314 (Princeton, NJ: Center for Energy and Environmental Studies, Princeton University, April 1999). Available as of January 2005, at: http://www.ransac.org/new-web-site/pub/reports/transparency.html.

regime was proposed for inspections of HEU components. The proposed agreement was never completed, however, in part because the two sides failed to negotiate a cooperative agreement to provide the legal basis for exchanging limited types of classified nuclear information.[34]

Exchange and Confirmation of Declarations on Total Stocks of NEM

As noted in Chapter 2, Presidents Clinton and Yeltsin agreed at their September 1994 summit and again at the summit of May 1995 that their governments would exchange detailed information on stocks of NEM as well as on inventories of nuclear weapons themselves. The May 1995 summit statement also called for an agreement on "other cooperative measures, as necessary to enhance confidence in the reciprocal declarations of fissile material stockpiles." And the March 1997 Clinton-Yeltsin summit statement mentioned yet again the desirability of exploring transparency measures for nuclear materials. The bilateral measures to increase transparency contemplated in these statements did not materialize by the end of the Clinton Administration, in part because there was no cooperative agreement to lift the secrecy restraints on the relevant information.[35] The Bush Administration has not pursued either warhead dismantlement transparency or comprehensive data exchanges relating to stockpiles of nuclear warheads and NEM, but in the context of the Moscow Treaty, has established a joint U.S.-Russian working group on transparency in offensive nuclear forces. As of early 2005, there had been no public statement that this group had agreed to pursue any particular transparency measures.

Transparency at Nunn-Lugar Storage Sites

For those Nunn-Lugar projects related to carrying out dismantlement required by arms control agreements—where Russia had already taken the decision to allow inspection as part of the nego-

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[34] Both the U.S. and Russian legal systems impose stringent requirements for protecting classified information related to nuclear weapons. In 1994 Congress amended the Atomic Energy Act to provide legal authority to negotiate an "Agreement for Cooperation" with Russia that would provide the legal basis for exchanging classified nuclear information (known under the act as "restricted data") for nonproliferation and arms control purposes. The two sides began negotiating such an agreement in 1995 and had it nearly completed by late 1995, but at that time the Russian government called off further talks pending a "policy review," and the talks have never resumed.

[35] See the Department of State's annual report on Moscow Treaty implementation, available as of January 2005, at: http://www.state.gov/t/ac/rls/or/25474.htm.

tiation of the initial agreement—problems of secrecy and access to the sites have generally not been unduly burdensome. This has not been the case, however, where no previous arms control requirement to allow access to the relevant sites or information exists, as is the case with most of the projects related to NEM.

In particular, the United States and Russia agreed in principle, early in the implementation of the Nunn-Lugar Cooperative Threat Reduction program, that transparency measures would be applied at the storage facility for surplus Russian weapon NEM that was then proposed to be built at Mayak with U.S. assistance. The negotiation of the details of these measures, however, has proven difficult. The overlap of three different proposed transparency regimes at this one facility—unilateral Nunn-Lugar transparency, bilateral MRI measures, and international IAEA verification—complicated negotiations considerably.

In recent years, although the focus has narrowed to just the unilateral Nunn-Lugar transparency, disagreements have continued, as Russia judged that a number of the measures the United States proposed would reveal information that is secret in the Russian system. As of January 2005, the Mayak facility has been completed, but the bilateral transparency arrangements are still not agreed. In the approach currently under discussion, the surplus plutonium will arrive in the form of spherical metal ingots contained in cans (prepared without U.S. assistance), on which external measurements will be made to verify that at least a threshold quantity of plutonium is inside each container, the fact that it is roughly weapon grade, and perhaps also the fact that it is in metallic form. Agreement has not been reached in part because Russian negotiators assert that the mass of plutonium stored at the facility is itself secret under Russian secrecy rules.[36] Earlier proposals by the United States for measurements of a larger number of attributes, and for monitoring of the "upstream" steps leading to the fabrication of the metal ingots were rejected by the Russian side—in part because the U.S. side offered no parallel monitoring of similar steps in the United States.

Monitoring Issues in Plutonium Production and Disposition

The 1997 U.S.-Russian agreement on ending production of weapons plutonium includes a requirement for monitoring meas-

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[36] Nuclear Threat Initiative, "Mayak Storage Facility Transparency," Monitoring Stockpiles. Available as of January 2005, at: http://www.nti.org/e_research/cnwm/monitoring/mayak.asp.

ures to confirm the shutdown status of those plutonium production reactors that are already shut down (all of the U.S. plutonium production reactors, and all Russian plutonium production reactors except for three that were also the principal regional sources of heat and electricity) and to confirm that plutonium produced in Russia's three remaining plutonium production reactors after 1994 would not be used in weapons.[37] To confirm that the plutonium offered for monitoring was in fact the plutonium produced in these reactors, the agreement specified that U.S. monitors would be able to take measurements to confirm that the ratio of Pu-240 to total plutonium and the ratio of Am-241 to Pu-241 were below certain thresholds (the former to confirm that the material submitted for monitoring was weapon-grade plutonium, and the latter to confirm that it had been recently separated). For years after the entry into force of the agreement, however, Russia and the United States could not agree on the specific monitoring measures for the stored plutonium that U.S. monitors should be allowed to implement, largely because of Russian concerns that more specific details of the isotopic characteristics of the plutonium than the ratios covered in the agreement, still considered classified in Russia, would be revealed. Since 2002, U.S. monitors have been allowed to conduct monitoring visits to the facilities where the plutonium is stored, but U.S. and Russian experts are still jointly developing measurement equipment that will allow appropriate measurements to be taken while addressing Russian concerns.[38]

Similarly, the 2000 U.S.-Russian Plutonium Management and Disposition Agreement specified that a variety of monitoring measures would be put in place to confirm that the material subject to disposition was weapon grade, that disposition actually took place, and that the material was not returned to weapons. Virtually no progress has been made in negotiating specifics of such monitoring arrangements. U.S. officials believe that these talks will not move forward until larger issues affecting the viability of the plutonium disposition effort are resolved, including international fi-

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[37] The text of the agreement is available as of January 2005, at: http://www.ransac.org/new-web-site/related/agree/bilat/core-conv.html.

[38] See, for example, the brief discussion on the official Web site of the Department of Energy's Warhead and Fissile Material Transparency Program, available as of January 2005, at: http://www.nnsa.doe.gov/na-20/wfmt.shtml.

nancing and management arrangements and a resolution of the U.S.-Russian dispute over liability in the event of an accident.[39]

Unilateral Openness Initiatives and Informal Cooperation

Somewhat offsetting the slow pace of negotiated bilateral increases in transparency, the United States has taken some unilateral initiatives to increase the openness of its nuclear activities, including those related to NEM. Information that has been declassified covers a broad range, from details of past radiation experiments on humans to data on the number of U.S. nuclear tests. In addition to the release of this information, visits to a wide range of nuclear facilities by the public and by Russian representatives have been permitted. As indicated earlier, however, the information the United States has declassified so far about its military stocks of NEM has been less than complete, and what has been made public up until now by Russia about its military NEM stocks is even less complete.

While Russia has not yet matched all of the U.S. openness initiatives, a significant increase in openness since the collapse of the Soviet Union is apparent. Particularly in the contexts of lab-to-lab cooperation on scientific projects and U.S.-Russian cooperation in securing and accounting for nuclear warheads and materials, Russia has allowed visits to a broad range of formerly secret nuclear sites. These visits and discussions, along with Russian visits to many U.S. nuclear sites, have created an unprecedented window to improve each nation's understanding of the other's nuclear complex and activities. Russia has also declassified full information on past Russian nuclear testing, paralleling the information the United States released earlier on its own nuclear testing program. Information on the size, locations, and characteristics of Russia's stockpiles of warheads and fissile materials remains classified at this writing.

The road to greater openness has by no means been a smooth one. In both Russia and the United States, high-level support for increased openness has often been countered by intense opposition from nuclear security bureaucracies. In Russia, a remarkable period of openness immediately following the collapse of the Soviet Union was followed by a struggle that continues to this day, as Russia's security services push to reassert control and limit access

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[39] Matthew Bunn, "Russian Plutonium Disposition," 2004, Reducing Excess Stockpiles. Available as of January 2005, at: http://www.nti.org/e_research/cnwm/reducing/rpdispose.asp.

to potentially sensitive sites and information, while U.S.-Russian cooperation continues to establish its value and expand. In the United States, the openness initiatives of the 1990s have given way, in the aftermath of the September 11th attacks, to substantial retrenchment, including attempts to reclassify material that was previously in the public domain.

Lab-to-lab Cooperation on Transparency Technologies

Building on the model of the material protection, control, and accounting (MPC&A) program—in which laboratory experts working directly together succeeded in demonstrating technology, building trust, and establishing a constituency to expand similar programs, eventually leading to new government-to-government agreements—U.S. and Russian laboratories began in 1994 a modest program to jointly develop and demonstrate transparency technologies. The first initiative in this effort was a demonstration of "remote monitoring," using video cameras and similar technologies to monitor material in storage, without requiring on-site inspectors. Equipment was hooked up to monitor HEU in storage at the Kurchatov Institute in Moscow, and at Argonne National Laboratory-West in Idaho, with the images and data uplinked via satellite.[40]

In subsequent years, the two sides have jointly developed and experimented with a range of technologies that could be applicable to confirming warhead dismantlement without revealing sensitive information, and to other transparency and monitoring tasks. These have included, for example, approaches to the use of templates and attributes to confirm the presence of nuclear warheads or of particular types of NEM in containers. Since the September 11th attacks, the focus of this lab-to-lab work has shifted to include detection of explosives and of nuclear materials for counterterrorism purposes.[41]

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[40] Robert L. Martinez, Dennis Croessmann, Vladimir Sukhoruchkin, Alexander Grigoriev, and Mark Sazhnev, "American-Russian Remote Monitoring Transparency Program: Accomplishments During the Past Year," in *Proceedings of the 38th Annual Meeting of the Institute of Nuclear Materials Management* (Northbrook, IL: Institute of Nuclear Materials Management, 1997).

[41] The Department of Energy maintains an official Web site describing this work, available as of January 2005, at: http://www.nnsa.doe.gov/na-20/wfmt.shtml. For other descriptions, see, for example, U.S. Department of Energy, Office of Nonproliferation and Nuclear Security, *Warhead and Fissile Material Transparency Program Strategic Plan* (Washington, DC: Department of Energy, May 1999) and the papers available at the Web site of the Applied Monitoring and Transparency Laboratory, available as of January 2005, at: http://amtl.iwapps.com.

Considerations and Options Looking Ahead

Limitations on NEM transparency between the United States and Russia constitute, in our judgment, the greatest current obstacle to strengthening U.S.-Russian cooperation on MPC&A and hence one of the principal barriers to reducing the danger that NEM will fall into the hands of terrorists, agents of proliferant states, or black marketeers who would sell to either.[42] The U.S. and Russian governments need to reach studied conclusions about the appropriate balance between secrecy and openness in the service of their national security interests, and then arrive at a common understanding that both can enforce within their national security establishments. The United States should decide what access to its own facilities it is willing to accept by the Russians, in exchange for the benefits of U.S. access to corresponding facilities in Russia.

In this connection, the U.S. government could update the detailed declaration released in the mid-1990s on the history of production and utilization of military Pu, leading to the current stockpile, and fulfill its promise to release similarly detailed information relating to U.S. military HEU. Correspondingly, the United States could encourage Russia to complete its own national inventories and histories for military Pu and HEU and to share this information with the United States, and preferably more widely. The United States and Russia could then proceed to demonstrate jointly and to deploy measures for helping to confirm the accuracy of these declarations, including exchanges and analysis of production records, the use of “nuclear archaeology” techniques, and spot checks of declared amounts at particular sites under conditions designed to protect information that remains sensitive. Here as elsewhere, some information considered particularly sensitive could be exchanged in encrypted or message digest form to be made available at a later date or on selective demand as discussed in Chapter 2 for sensitive weapons information.

Reciprocity in these activities could have a beneficial effect on the programs. It could, for example, be important to accelerate im-

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[42] See Matthew Bunn, Anthony Wier, and John P. Holdren, *Controlling Nuclear Warheads and Materials: A Report Card and Action Plan* (Washington, DC: Nuclear Threat Initiative and the Project on Managing the Atom, Harvard University, March 2003) and John Holdren and Nikolai Laverov, *Letter Report from the Co-Chairs of the Joint Committee on U.S.-Russian Cooperation on Nuclear Non-Proliferation*. The U.S. National Academies and the Russian Academy of Sciences, February 2003. Available as of January 2005, at:
http://www4.nationalacademies.org/news.nsf/isbn/s02052003?OpenDocument.

plementation of existing material protection projects across the Russian nuclear complex, a goal to which the United States is committed. It could also be vital for ensuring progress at certain highly sensitive sites, such as Russia's two main warhead production and maintenance facilities. If the United States and Russia agree to proceed with reciprocity in this arena, then a clear and agreed definition of the measures, and a description of the rationale for them, would increase the probability of success.

In pursuing the appropriate kinds and degrees of transparency for these purposes, it will be important to be attentive to the advantages and disadvantages of public versus classified exchanges between the two governments. Indeed, it will be necessary to think carefully about what kinds of information would be shared only between the United States and Russia, what kinds shared only with the NPT-authorized nuclear weapon states as a group, what kinds shared with all governments in good standing under the NPT, and which kinds made public.[43]

International Monitoring of Excess Military NEM

Some progress toward placing excess U.S., Russian, and possibly other NEM under international monitoring to verify for the world that it is never again returned to weapons—a step recommended reports from both The National Academies and Independent Bilateral Scientific Commission[44]—was made in the years after those reports were published, but that progress has now essentially ground to a halt.

Declarations of Excess Material

In 1995 President Clinton declared that some 225 tons of U.S. NEM was excess to U.S. military needs, and would no longer be available for military use. As the details were provided subse-

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[43] There are many nuances in all this; for example, information that was to remain classified could, in principle, be provided to other governments without a formal cooperative agreement if the classification level of the material were merely "secret" rather than "restricted data" or "formerly restricted data."

[44] See National Academy of Sciences, Committee on International Security and Arms Control, *Management and Disposition of Excess Weapon Plutonium*, 2 vols. (Washington, DC: National Academy Press, 1994 and 1995); Steve Fetter, *Verifying Nuclear Disarmament*, Occasional Paper 29, Henry L. Stimson Center, Washington, DC, 1996; and Independent Bilateral Scientific Commission on Plutonium Disposition, *Final Report,* Washington, DC: President's Committee of Advisors on Science and Technology, The White House, and Russian Academy of Sciences, June 1997.

quently, this figure increased somewhat: total U.S. excess declarations include 52.5 tons of plutonium and 174 tons of HEU. This represented slightly more than half of the plutonium stockpile that the U.S. departments of Energy and Defense possessed, but a much smaller fraction of the HEU stockpile – because the U.S. Navy reserved nearly all HEU that met its quality standards for future use as naval fuel. In 1993 Russia had agreed to sell the United States LEU blended from 500 tons of its weapons-grade HEU—effectively declaring this HEU excess to its military needs—and in 1996-1997 Russia responded to Clinton's declaration by declaring that "up to" 50 tons of plutonium, along with 500 tons of HEU, was excess to its military needs. The Russian declaration represented a smaller fraction of Russia's total stockpile of separated plutonium, but a larger fraction of Russia's stockpile of HEU, compared with the U.S. declaration. (It is notable that from the beginning there was no effort to negotiate how much NEM should be declared excess and how much should remain in each country's military stockpile; this was left entirely as a matter for unilateral determinations and declarations.) Years later, the United Kingdom followed suit, declaring that 4.4 tons of its plutonium stockpile (including 0.3 ton of weapons-grade plutonium) was excess to its military needs, along with large quantities of uranium (though no HEU).[45]

Initiatives, Agreements, and Obstacles

In September 1993 President Clinton announced that the United States would make its excess fissile material eligible for IAEA safeguards in order to assure the world that these materials were not being used for nuclear weapons. Classification issues, budget constraints, and safety concerns related to monitoring material in radioactive facilities, however, have slowed progress on this front. As of early 2003, 12 tons of the U.S. excess military NEM was under IAEA safeguards (10 tons of HEU and 2 tons of plutonium), and the IAEA had verified the down blending of more than 20 additional tons of U.S. HEU. IAEA monitoring is in place for the continuing blend-down of excess U.S. HEU at BWX Technologies in Lynchburg, Virginia.[46]

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[45] See Matthew Bunn, "IAEA Monitoring of Excess Nuclear Material," Monitoring Stockpiles. Available as of January 2005, at: http://www.nti.org/e_research/cnwm/monitoring/trilateral.asp.

[46] Ibid.

At the Moscow Nuclear Safety and Security Summit in 1996, the assembled leaders agreed that excess fissile material should be placed under international safeguards as soon as it is practicable to do so. On that occasion, Russian President Yeltsin made a commitment to place the storage facility being built at Mayak, which was then expected to hold an estimated 50 tons of plutonium and a much larger amount of HEU, under IAEA safeguards,[47] but this pledge has not yet come to fruition. The United Kingdom has made its excess nuclear material eligible for international safeguards; while the IAEA has not had the resources to apply safeguards to this material, it is under EURATOM safeguards.

The Trilateral Initiative

There is consensus among the IAEA, the United States, and Russia that putting excess military NEM under IAEA oversight represents a fundamentally new mission for that international agency: namely verifying nuclear disarmament in nuclear weapon states possessing many weapons, rather than verifying nonproliferation in non-nuclear weapon states. Consequently, new terminology ("verification" rather than "safeguards") and new approaches should be used. In September 1996, following up on the Clinton and Yeltsin pledges to allow the IAEA to verify excess NEM, the United States, Russia, and the IAEA established a "Trilateral Initiative" to discuss the broad range of issues related to placing excess military NEM under IAEA verification.

During several years of work, U.S. and Russian scientists developed and tested approaches to allow the IAEA to confirm that plutonium objects in containers had certain attributes of weapons components (e.g., at least a threshold mass of plutonium, at least a threshold ratio of Pu-239 to total plutonium, plutonium in metallic form, a generally symmetric shape), without revealing classified information. Legal experts worked out an approach to a new agreement that would no longer allow the United States and Russia to remove the material from verification at any time, as their vol-

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[47] Because excess HEU from dismantled weapons is being processed to LEU for sale to the United States, Russia does not plan to store HEU at Mayak. Moreover, Russia currently plans to store only 25 tons of plutonium at Mayak: the 34 tons of excess weapons plutonium covered by the U.S.-Russian Plutonium Management and Disposition Agreement, minus the roughly 9 tons of that material that is plutonium oxide produced since 1994, is in storage at Seversk and Zheleznogorsk. See Matthew Bunn, "Mayak Fissile Materials Storage Facility," Securing Nuclear Warheads and Materials. Available as of January 2005, at: http://www.nti.org/e_research/cnwm/securing/mayak.asp and the discussion above in the section on "Monitoring Issues in Plutonium Production and Disposition."

untary safeguards agreements with the IAEA do. A number of options for financing such IAEA verification activities were explored.

At the IAEA General Conference in September 2002, the parties issued a statement in which they "declared victory" on the initiative, contending that they had successfully developed a regime, and demonstrated techniques that would make it possible to put plutonium in classified forms under international verification. In reality, however, the effort came nearly to a halt without coming to fruition, as (a) neither the United States nor Russia has yet agreed to put any nuclear material under this type of verification;[48] (b) agreement remained elusive on whether IAEA monitoring would continue on the material until it met standard IAEA "safeguards termination" criteria (i.e. the point at which the IAEA no longer monitors material, such as NEM in nonrecoverable waste);[49] and (c) there was no agreement on who would pay for such verification.

The 2000 U.S.-Russian Plutonium Management and Disposition Agreement includes a provision requiring each party to begin consultations with the IAEA "at an early date," and to conclude agreements with the IAEA to allow it to conduct verification beginning "not later in the disposition process" than when the plutonium has been processed to an unclassified form and is placed in storage at a conversion or conversion/blending facility, or when it is received at a fuel fabrication or immobilization facility (whichever is sooner). This is now expected to be the future focus of activities related to IAEA monitoring of U.S. and Russian excess plutonium, but neither the United States nor Russia has begun serious discussions with the IAEA concerning such verification. (As noted earlier, even U.S.-Russian discussions of bilateral transparency for the disposition process have not yet gotten seriously underway.)

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[48] The United States has not been willing to commit to placing any of its excess plutonium that was in the form of classified weapons components under verification, and in the absence of such a commitment, there is little hope of getting such a commitment from Russia, where the vast majority of the plutonium declared excess is believed to be in that form.

[49] This condition would have the effect, if Russia used the material as MOX and then reprocessed that MOX for recycle as it plans to do, of ultimately subjecting Russia's entire civilian nuclear infrastructure to IAEA inspections. Russia proposes instead that IAEA verification should end once material has left a storage facility and been converted to reactor fuel.

Considerations and Options Looking Ahead

We believe that world confidence in the reality and irreversibility of U.S. and Russian nuclear arms reductions would benefit from multilateral rather than merely bilateral monitoring of the excess stocks of NEM. If nuclear arms reductions proceeded to the point that nuclear weapon states other than the United States and Russia see fit to declare some of their military NEM as surplus to military needs, having an established international monitoring operation for such materials already in place would be very advantageous. We believe that both for monitoring the current U.S. and Russian surpluses and for potential extension to surplus military NEM in other states, using the stature, experience, and capabilities of the IAEA is a better option than trying to construct a new multilateral verification institution.

Establishing the capacity of the IAEA to discharge this function for the U.S. and Russian surplus NEM now, and for other surpluses later, would require strengthening of the agency to deal with a set of responsibilities that has been expanding in relation to civil NEM and the detection of clandestine nuclear weapon programs. The costs of the IAEA safeguarding the excess NEM in the United States and Russia would be small by security standards but large in the context of the IAEA budget. The United States and Russia could take responsibility for IAEA's costs for this mission; seek to mobilize a wider coalition of the IAEA member states most interested in verified disarmament to share the costs; seek agreement on mandatory contributions to a special fund for this purpose from all IAEA member states; or propose other financing mechanisms. This funding should be considered a separate matter from the needed increases in the IAEA budget for its expanded safeguards functions for civil NEM.

Transparency and Monitoring for Civil NEM

The measures currently in place for implementing international transparency with respect to civil NEM are principally those negotiated by the IAEA under Safeguards Agreements with individual non-nuclear weapon states, pursuant to the requirement of the NPT. The public transparency thus generated is limited, inasmuch as IAEA rules do not permit sharing most of the information it develops in its safeguards programs with the world community. Moreover, the 1957 EURATOM Agreement, which predates the NPT and the IAEA, provides for safeguarding of civil NEM in the countries of the European Community, but EURATOM, like the IAEA, does not reveal the information developed in its safeguards activities. The issue of public openness of transparency deserves careful review, as the release of some information could be helpful in building confidence and laying a foundation for further steps in the control of NEM, while the release of other information could aid potential proliferators and terrorists or create counterproductive political problems

Traditional IAEA Responsibilities and Methods

Traditional IAEA safeguards are designed to detect Significant Quantities of nuclear material with "high confidence" and in a "timely manner."[50] As noted above, the IAEA defines a Significant Quantity as 8 kilograms of plutonium or U-233, or 25 kilograms of U-235 in HEU. "High confidence" is usually taken to mean 90 percent or more probability of detecting diversion of the defined Significant Quantity. The definition of "timely" is based on, but not necessarily identical to, the IAEA's estimate of the time a proliferant state would need to convert the diverted material into a finished weapon component. For HEU or separated plutonium metal, the IAEA sets this time at 7-10 days; for NEM in forms such as pure oxides or other compounds, mixed compounds, or scrap, the estimate is 1-3 weeks. In reality the "conversion time" could be less or more depending on the amount of advance preparation for weaponization.[51]

The IAEA audits each country's records of nuclear material inventories and the changes in these inventories that occur in each relevant facility, and collects data to verify the accuracy of those records. IAEA inspectors measure and estimate amounts of nuclear material, count discrete items such as fuel rods, affix tags and seals to track whether items have been moved or tampered with, and install and monitor video cameras and radiation detectors to track activity around and movement of the relevant items and materials.

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[50] See IAEA, *IAEA Safeguards Glossary,* 2001 Edition (Vienna: International Atomic Energy Agency, 2002). Available as of January 2005, at: http://www-pub.iaea.org/MTCD/publications/PDF/nvs-3-cd/Start.pdf.; Steve Fetter, *Verifying Nuclear Disarmament*, Occasional Paper 29, Henry L. Stimson Center, Washington, DC, 1996; and Office of Technology Assessment, United States Congress, *Nuclear Safeguards and the International Atomic Energy Agency*, OTA-ISS-615 (Washington, DC: U.S. Government Printing Office, June 1995).

[51] See IAEA, *IAEA Safeguards Glossary,* 2001 Edition (Vienna: International Atomic Energy Agency, 2002). Available as of January 2005, at: http://www-pub.iaea.org/MTCD/publications/PDF/nvs-3-cd/Start.pdf.

Inspectors are also supposed to compare the design of proliferation-relevant facilities (such as uranium enrichment plants, fuel fabrication plants, and spent-fuel reprocessing plants) with the actual construction in order to verify their capacities and the flows of materials within them, and to evaluate the measurement systems used by the operators. The frequency of inspections depends on the quantity and weapon relevance of the nuclear material.

The traditional approach to IAEA safeguards was negotiated in the early 1970s, when most states believed that nuclear energy would be fundamental to their energy economies, and the non-nuclear weapon states were quite concerned that the requirement to accept IAEA safeguards should not put them at a commercial disadvantage in this key technology, in competition with the weapon states, who faced no such inspection requirement. As a result, the traditional safeguards regime was intentionally designed to be focused almost exclusively on declared nuclear sites, and within those on agreed "strategic points" for monitoring the nuclear material. In traditional safeguards agreements, the IAEA is explicitly required to collect only the minimum information needed to carry out its responsibilities under the agreement. In practice, the pressure from member states that IAEA inspections not be unduly intrusive created a situation in which the IAEA virtually never attempted to use the vague authority it was given in traditional agreements to request special inspections at undeclared sites.

Expanding Responsibilities and Reducing the Mismatch Between Authority and Resources

Whether the tools and authority of the IAEA and its inspectors are adequate in practice to meet its stated obligations has long been questioned by outside analysts and indeed by IAEA officials themselves.[52] New attention was focused on this question when inspections in the aftermath of the 1991 Gulf War confirmed that Iraq had pursued an extensive nuclear weapon program while a non-nuclear weapon state member of the NPT subject to IAEA safeguards. Deficiencies in the IAEA's operating capabilities were highlighted by the agency's focus on declared NEM facilities, its failure to exploit even its weak authority to conduct inspections of suspect undeclared facilities, and its inability (under the agency's

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[52] An account of these concerns is in Office of Technology Assessment, United States Congress, *Nuclear Safeguards and the International Atomic Energy Agency*, OTA-ISS-615 (Washington, DC: U.S. Government Printing Office, June 1995).

current operating rules) to focus inspection efforts preferentially on states of particular proliferation concern.

As a consequence, the IAEA developed new safeguards measures in its 93+2 program. These measures were incorporated in the voluntary "Additional Protocol" to the agency's safeguards agreements with individual states to provide added confidence that nuclear material has not been diverted from openly declared civilian activities, and that there are no undeclared hidden nuclear weapons activities. For each state that agrees to the Additional Protocol, these new measures include:[53]

- An expanded declaration covering a detailed description of the state's entire nuclear program (not just the activities involving nuclear materials, which already must be declared under existing IAEA agreements set forth in INFCIRC/153); declarations, including blueprints, of new facilities before construction begins; information on the import-export of certain equipment and material; and an outline of nuclear fuel cycle plans for the coming 10 years;
- broader physical access to declared locations and facilities, not restricted to agreed "strategic points" as in INFCIRC/153, and improved explicit access to suspicious undeclared locations, including environmental monitoring for detection of proscribed activities;
- improved procedures for getting inspectors in and information out, including restrictions on a state's ability to reject particular inspectors, a requirement that states issue multi-entry visas to inspectors, reductions in the advance notice of inspections that must be provided to the host state, and allowance for direct communication by inspectors to IAEA headquarters or regional offices and for direct transmission of information from surveillance and measurement devices.

For those states that implement the Additional Protocol, the IAEA prepares an overall assessment of the nuclear activities of the state, and attempts to draw conclusions not only as to whether there has been any diversion of NEM from declared facilities—the traditional focus of IAEA safeguards—but also as to whether there

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[53] See IAEA, INFCIRC/540 - *Model Protocol Additional To The Agreement(S) Between State(S) And The International Atomic Energy Agency For The Application Of Safeguards* (Vienna: International Atomic Energy Agency, September 1997). Available as of January 2005, at: http://www.iaea.org/Publications/Documents/Infcircs/.

are any significant undeclared nuclear activities. Once the IAEA has had time to examine all the relevant information and draw the conclusion that there is no evidence of undeclared activities, it then begins to implement "integrated safeguards," an approach combining the traditional and new measures with the openness resulting from the new measures, making it possible to reduce the intensity of the older measures (such as the frequency of inspections at particular types of facilities). In the negotiation of the Additional Protocol, a tacit understanding was reached that after an initial pulse of increased expenditure, the new measures should be cost neutral, that is, that in general every dollar spent on the new measures should be matched by a dollar cut from traditional measures. Whether this is wise, and how much reduction in the intensity of traditional measures is justified, remain the subjects of controversy—though the specific integrated safeguards inspection approaches for most types of nuclear facilities are now agreed.

A substantial driver behind this controversy has been the budget picture. From 1986 to 2003, the IAEA was not permitted any real growth in its budget (as part of a more general effort to restrain cost growth of agencies within the U.N. system), even though the number of parties to the NPT increased substantially, the number of Significant Quantities of material under safeguards increased more than threefold, and new expenditures were required to implement the new safeguards approach. The IAEA's budget for safeguards worldwide, including both its regular budget and extrabudgetary contributions, amounts to roughly $100 million. This amount, which was insufficient for the agency's original mission, is plainly entirely inadequate now and will become increasingly so in the future. In 2003 the IAEA Board of Governors and General Conference approved a $19.4 million increase in the IAEA's safeguards budget, to be phased in over four years.[54] Nevertheless, in virtually every part of the IAEA's safeguards and security operations, limited resources remain an important constraint.

Access to information is as important as access to resources. With the advent of the Additional Protocol and the requirement that the IAEA prepare integrated assessments of the nuclear activities of each state, it has been widely accepted that the IAEA will seek information from open sources (such as newspaper accounts) and from member states, including their intelligence agencies**.** The

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[54] See, for example, IAEA, "IAEA Board of Governors Recommends Landmark Budget Increase," PR/2003/12 (Vienna: International Atomic Energy Agency, July 18, 2003). The $19.4 million figure for the amount of the increase devoted to safeguards was provided by a senior IAEA official.

amount of information available to the IAEA from intelligence sources remains very limited, however, and increased sharing of information could significantly increase the IAEA's effectiveness. Similarly, we judge that it would be extremely valuable for the nuclear supplier states to provide information to the IAEA on all approved nuclear or dual-use transfers, all denials of such transfers, and all cases of illegal transfers or attempted transfers, to give the IAEA a complete picture of the procurement activities of NPT parties.

A gap in the IAEA's authority is the fact that the five nuclear weapon states as defined under the NPT have no obligation to place either their military or their civilian NEM under IAEA safeguards, although they may do so voluntarily. As noted above, voluntary commitments by the United States and Russia to place NEM under IAEA safeguards have so far been very limited and slow to be put into effect. Although the United States has offered to place all of its civilian nuclear energy facilities under IAEA safeguards, the IAEA has understandably chosen not to spend its limited resources safeguarding these U.S. facilities on the grounds that it was highly unlikely a country with so many nuclear weapons and no prohibition on producing additional military NEM would divert civil NEM to make more weapons. British and French civil nuclear facilities are covered by safeguards agreements implemented by EURATOM, and a few civil facilities in these countries are also inspected by the IAEA. As of the end of 2001, the IAEA was applying safeguards to one nuclear power plant and one uranium enrichment plant in China, and one civil NEM storage facility in Russia.[55]

Considerations and Options Looking Ahead

We believe that broadening and strengthening the IAEA's safeguards activities is the most urgent and important agenda item in the category of enhancing multilateral transparency. Such an effort could include, as a start, full implementation of the innova-

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[55] IAEA, "Annual Report" 2001 (Vienna: International Atomic Energy Agency, 2002). Available as of January 2005, at: http://www.iaea.org/Publications/Reports/Anrep2001/. The IAEA's voluntary offer agreements with the UK, the United States, France, Russia, and China are described in IAEA INFCIRC document numbers 263, 288, 290, 327, and 369, respectively, available as of January 2005, at: http://www.iaea.org/Publications/Documents/Infcircs/

tions and extensions in safeguards practices developed in the IAEA's 93+2 Program and embodied in the Additional Protocol.[56]

At present, acceptance of the Additional Protocol is strictly *voluntary*. Nevertheless, in early 2005 there were 91 signatories to the Additional Protocol and 68 countries in which it was actually in force or being provisionally applied.[57] In February 2004 President Bush proposed that the Nuclear Suppliers Group (NSG), whose members have long required that states accept full-scope IAEA safeguards as a condition of supply, also require states to adopt the Additional Protocol as a condition of supply. At the summit of the Group of Eight (G8) industrialized democracies at Sea Island, Georgia, in June 2004, the G8 leaders endorsed this approach. The NSG has not yet reached consensus on such a requirement, but it is to be hoped that they will do so soon.

A further step could be a decision to make the Additional Protocol a *mandatory* requirement for all states party to the NPT. This would greatly strengthen the IAEA's effectiveness. Such a decision would probably require action by the U.N. Security Council (which has the power to make law binding on all states to deal with threats to international peace and security), or an agreed interpretation of the NPT, which might be made at the 2005 Review Conference or a subsequent conference. Making the Additional Protocol mandatory could be more politically acceptable to some states concerned with the discriminatory nature of the NPT if it were also mandatory on the nuclear weapon state parties to the NPT, and if it were coupled with mandatory verification of those states' civil nuclear activities.

Further, the United States and other states that make substantial investments in collection of nuclear-related intelligence could substantially increase the fraction of the information available to them that they provide to the IAEA, putting the information in a form

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[56] IAEA, INFCIRC/540 - *Model Protocol Additional To The Agreement(S) Between State(S) And The International Atomic Energy Agency For The Application Of Safeguards* (Vienna: International Atomic Energy Agency, September 1997). Available as of January 2005, at: http://www.iaea.org/Publications/Documents/Infcircs/.

[57] See IAEA, "Strengthened Safeguards System: Status of Additional Protocols" (Vienna: International Atomic Energy Agency, June 16, 2004). Available as of January 2005, at: http://www.iaea.org/OurWork/SV/Safeguards/sg_protocol.html. Ninety states have signed the protocol, as has Taiwan, which in IAEA practice does not count as a state. EURATOM is also an institutional party, and all the EURATOM states are now parties. The figure of 68 includes 65 states where the protocol is in force; Taiwan, where it is also in force; and Libya and Iran, where it is being provisionally applied.

that will not compromise sources and methods, and is designed to support the IAEA's efforts to develop an integrated picture of the nuclear activities of each non-nuclear weapon state party to the NPT and the Additional Protocol. As noted above, we believe that states should also make a commitment to provide the IAEA information on all nuclear and dual-use exports, denials of exports, and cases of illegal exports or attempted exports.

There is also more to be done to provide the IAEA the resources it needs, including both the need to finance IAEA verification activities in nuclear weapon states, and the IAEA's ongoing safeguards activities in non-nuclear weapon states. A substantially bigger budget increase will be required if the IAEA is to fulfill the dramatic increase in verification activities and obligations it is now being called upon to implement and do so effectively. At the same time, additional resources would also be needed for the IAEA's Nuclear Security Fund, including both greater voluntary contributions and consideration of including at least a portion of the IAEA's nuclear security activities in the regular budget, paid for through mandatory assessments from member states.

The adequacy of the IAEA's values for "Significant Quantities" of NEM and for what constitutes "timely detection" could be reexamined periodically in light of the probable spread of sophisticated knowledge of nuclear weapon design concepts and fabrication techniques. Regardless of the outcome of such reviews, confidence in monitoring and providing "timely detection" could be increased by expanded application of near-real-time accountancy in the most sensitive facilities, notably enrichment and fuel-reprocessing plants, which could be achieved by using the Internet or satellite uplinks to relay information from sensors inside the plants directly to IAEA headquarters.[58]

REDUCING NEM STOCKS, FLOWS, AND SITES

The preceding sections have treated the approaches, obstacles, and possibilities for NEM transparency and monitoring in a largely qualitative way, that is, without specific reference to the quantitative measures (total stocks of materials, rates of production and

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[58] See Steve Fetter, *Verifying Nuclear Disarmament*, Occasional Paper 29, Henry L. Stimson Center, Washington, DC, 1996 and for a more extensive and recent treatment, Thomas E. Shea, "Potential Roles for the IAEA in a Warhead Dismantlement and Fissile Materials Transparency Regime," in N. Zarimpas, ed., *Transparency in Nuclear Warheads and Materials* (New York: Oxford University Press and Stockholm International Peace Research Institute, 2003), pp. 229-249.

disposition, numbers of sites) that bear on both the motivation for and the difficulty of transparency and monitoring for these materials. The real and perceived risks of breakout, diversion, and theft at the core of concerns about NEM tend to grow, all else being equal, in various proportions to these quantitative factors. Breakout and diversion concerns rise with total stocks, flows, and potential flows in the form of production capacity; theft concerns rise mainly with number of sites (on the supposition that more sites are more difficult to guard, given limited resources) and with flows that provide opportunities for thieves. In addition, transparency and monitoring tend to be more easily accomplished—again, all else being equal—the lower the number of sites and the smaller the sizes of the stocks and flows. All this motivates interest in reductions in sites, stocks, and flows as one way to reduce real and perceived risks and to ease the tasks of transparency and monitoring. But the processes of reduction in stocks and sites can themselves lead to increased requirements for transparency and monitoring (in response to international demand for reassurance that the reductions are real).

Total stocks of NEM, whether military or civilian, can be reduced from what they would otherwise be by reducing the rate at which these materials are produced and/or by increasing the rate at which they undergo final disposition (blenddown to LEU in the case of HEU and irradiation/burnup or immobilization/isolation in the case of plutonium). The flows of NEM, meaning the frequency and quantity of transfers from one location to another, depend on rates of production, use, and disposal, as well as on choices about technology and about approaches to materials management.

The remainder of this section focuses on the principal processes for reducing NEM stocks, flows, and sites, namely, the conversion of research reactors to run on LEU rather than HEU; choice and management of civil nuclear energy technologies to minimize NEM stocks, flows, and sites; actions to consolidate NEM at fewer sites; cutoff of production of NEM for weapons; and final disposition of HEU and plutonium. In each case, issues relating to transparency and monitoring are identified, the current status discussed, and consideration is given to options looking forward.

Conversion of Research Reactors from HEU

An important form of dispersed HEU stocks could be eliminated altogether if the use of HEU in research reactors were phased out worldwide. As seen in Table 3-2 above, these facilities contain altogether about 20 metric tons of HEU, much of it only lightly irradiated (hence relatively easy to process to remove the fission products) and some not irradiated at all. Most research reactors that use HEU are capable of operating with redesigned fuel that uses LEU instead. Alternatively, research reactors that are obsolete or unneeded could be shut down—and their HEU removed—as a way to complete the elimination of this "target of opportunity" for diversion to terrorists and proliferant states.

History, Status, and Transparency Issues

Recent estimates indicate that around 135 research reactors worldwide continue to operate with HEU. In addition, a number of HEU-fueled research reactors that have been shut down still have HEU stored at the reactor site.[59] The majority of these research reactors were originally supplied by the United States, nearly all of the rest by the Soviet Union/Russia.

For the past 25 years, the U.S. Reduced Enrichment for Research and Test Reactors (RERTR) program has been developing proliferation-resistant low enriched fuels to replace HEU fuel in research reactors and helping U.S. and U.S.-supplied reactors convert. Scores of reactors have successfully converted, many more HEU-fueled reactors have ceased operation, and some tons of (mostly irradiated) HEU fuel have been shipped back to the United States. A new LEU-molybdenum fuel compatible with almost all of the research reactors in the world today has recently been developed by Argonne National Laboratory and is expected to be licensed and available for purchase by around 2010.[60] At the same time, however, one new research reactor using HEU has recently been constructed in Germany.

In recent years, the United States has been pursuing several separate programs to reduce security threats posed by HEU at research reactors and related or similar facilities. As just noted, there is a quarter-century-old effort to help U.S.-supplied research reactors convert to LEU fuels, and to develop and implement LEU targets for medical isotope production. This program has begun coop-

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[59] See Matthew Bunn, Anthony Wier, and John P. Holdren, *Controlling Nuclear Warheads and Materials: A Report Card and Action Plan* (Washington, DC: Nuclear Threat Initiative and the Project on Managing the Atom, Harvard University, March 2003), pp. 131-32 and references therein.

[60] See Matthew Bunn and Anthony Wier, "Converting Research Reactors," on the *Controlling Nuclear Weapons and Materials* section of the Nuclear Threat Initiative Web site. Available as of January 2005, at: http://www.nti.org/e_research/cnwm/securing/convert.asp.

eration with Russia to develop fuels so that Soviet-supplied research reactors can be converted to LEU as well.[61] At the same time, the United States is seeking to take back HEU fuel that it supplied from sites around the world, an effort that was restarted in 1996. This is an essential element of the RERTR program, inasmuch as the offer to take the spent fuel off reactor operators' hands if they would agree to convert to LEU is a key incentive for the operators to convert. Both the conversion effort and the U.S. take-back effort have typically focused on reactors with one megawatt of thermal power or more, which need regular supplies of fresh HEU fuel, but lower-power facilities such as critical assemblies and pulsed power facilities also often have substantial quantities of HEU on-site.

The United States, Russia, and the IAEA have launched a tripartite initiative to take back Soviet-supplied HEU located at vulnerable sites around the world to secure facilities in Russia, where, in most cases, it is to be blended to LEU.[62] Separate efforts, sometimes pursued bilaterally and sometimes through the IAEA, have been pursued to upgrade security for HEU at such sites without removing it. In addition, over the years several high-profile removals of HEU from potentially vulnerable facilities have been organized as separate efforts, not directly part of any of these initiatives, including Project Sapphire (the removal of almost 600 kilograms of HEU from Kazakhstan in 1994), Operation Auburn Endeavor (the removal of a few kilograms of fresh and irradiated HEU from the former Soviet republic of Georgia in 1998), and Project Vinca (the removal of 48 kilograms of 80 percent enriched HEU from a facility near Belgrade in the former Yugoslavia in 2002). Following the Vinca effort, in the U.S.-Russian-IAEA initiative, HEU has been removed from Romania, Bulgaria, and Libya.

This approach of addressing the security dangers posed by vulnerable HEU in many separate programs with different manage-

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[61] A Soviet RERTR program had started in the 1970s, but was terminated in the course of the collapse of the Soviet Union. See, e.g., Oleg Bukharin, Christopher Ficek, and Michael Roston, "U.S.-Russian Enhanced Research and Test Reactor (RERTR) Cooperation," Russian-American Nuclear Security Advisory Council, Princeton University, 2003; Alexander Vatulin et al., "Progress of Russian RERTR Program: Development of a new type of fuel element for Russian-built research reactors," paper presented at the International Conference on Research Reactor Fuel Management (RRFM 2002) Ghent, Belgium, March 17-20, 2002.

[62] See Matthew Bunn and Anthony Wier, "Converting Research Reactors," Securing Nuclear Warheads and Materials. Available as of January 2005, at:
http://www.nti.org/e_research/cnwm/securing/convert.asp.

ment and approaches unfortunately left a number of important gaps. As just one of several examples, two-thirds of U.S.-supplied HEU abroad was not covered by the U.S. HEU take-back program as originally structured, and the incentives offered for facilities to send their HEU back to the United States were sufficiently limited that, as of early 2004, half of the material that was covered in the program was not expected to return.[63] Recognizing this problem, in May 2004 U.S. Secretary of Energy Spencer Abraham announced the Global Threat Reduction Initiative (GTRI), which consolidates all of these efforts, and is intended to provide a comprehensive approach to securing and removing NEM (and related equipment, as well as radiological material) from small, potentially vulnerable sites around the world.[64] The new Department of Energy Office of Global Threat Reduction is in the process of fleshing out the details of the new initiative.

Considerations and Options Looking Ahead

We judge that the problems posed by HEU-fueled research reactors for monitoring related to nuclear arms control, nuclear nonproliferation, and protection against nuclear terrorism would be most effectively addressed by completing as expeditiously as possible the conversion to LEU of all such reactors that are convertible and still worth operating and shutting down the rest. A number of specific steps could be taken in this direction.

As part of wider efforts to consolidate NEM at fewer sites (see below), the HEU from all converted and shut-down research reactors could be removed to centralized sites where its storage can be

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[63] See DOE, Office of Inspector General, *Audit Report: Recovery of Highly Enriched Uranium Provided to Foreign Countries,* DOE/IG-O638 (Washington, DC: Department of Energy, February 2004). Available as of January 2005, at: http://www.fas.org/irp/agency/doe/ig-heu.pdf. For more on the gaps that existed in U.S. efforts as of early 2004 see Matthew Bunn and Anthony Wier, *Securing the Bomb: An Agenda for Action* (Washington, DC: Nuclear Threat Initiative and the Project on Managing the Atom, Harvard University, May 2004), pp. 58-59.

[64] For accounts of the GTRI, see Spencer Abraham, remarks to the IAEA, Vienna: May 26, 2004. Available as of January 2005, at: http://www.energy.gov/engine/content.do?PUBLIC_ID=15949&BT_CODE=PR_SPEECHES&TT_CODE=PRESSSPEECH; Spencer Abraham, remarks to the Eisenhower Institute, Washington, DC, June 14, 2004. Available as of January 2005, at: http://www.energy.gov/engine/content.do?PUBLIC_ID=16020&BT_CODE=PR_SPEECHES&TT_CODE=PRESSSPEECH; and U.S. Department of Energy, "Global Threat Reduction Initiative Highlights," March 26, 2004. Available as of January 2005, at: http://www.energy.gov/engine/doe/files/dynamic/264200491138_Vienna_GTR_Fact%20Sheet_FINAL1_052604%20.pdf.

more secure and its monitoring (preferably international) can be more reliable than at the dispersed research reactor sites. In this connection, it would be important to ensure that the new GTRI is pursued rapidly, comprehensively, and flexibly, in particular with a focus on providing adequate incentives, targeted to the needs of each facility, for facilities to give up the HEU at their sites. Funding could be increased to speed the availability of the advanced replacement LEU fuel expected to make it possible to convert all remaining research reactors that it makes sense to continue to operate. Take-back efforts for HEU fuel could be accelerated, with new attention to provision of incentives for participation by facilities that do not require fresh fuel or spent fuel management. And the tripartite U.S.-Russia-IAEA initiative for take-back of fuel from Russian-supplied research reactors could be pushed ahead. There is little monitoring difficulty and no security trade-off because the facilities involved are not sensitive from a military standpoint.

In addition to research and medical isotope production reactors, HEU-fueled reactors in submarines, surface warships, and icebreakers could be looked at more closely with respect to the problems their fueling systems and their spent fuel could pose for a more comprehensive regime of controls and monitoring for NEM.[65] The case of naval reactors is clearly far more sensitive and difficult than that of research reactors from the standpoint of both performance trade-offs and protection of classified information during monitoring but appears to be manageable on a cooperative basis.

Minimizing NEM Stocks, Flows, and Sites in Civil Nuclear Energy Generation

NEM can play a role in the normal operation of civil nuclear energy systems in two ways: reactor designs that require (or "prefer") the use of fresh fuel made from NEM and the choice of reprocessing of spent fuel (from a reactor of any design) in order to separate NEM from fission products and other diluents in the spent fuel. The first is a choice about the "front end" of the fuel cycle; the second is a choice about the "back end," although it usually

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[65] See John Holdren and Nikolai Laverov, *Letter Report from the Co-Chairs of the Joint Committee on U.S.-Russian Cooperation on Nuclear Non-Proliferation*. The U.S. National Academies and the Russian Academy of Sciences, February 2003. Chunyan Ma and Frank von Hippel, "Ending the Production of HEU for Naval Reactors," *Nonproliferation Review* 8 (Spring 2001), p. 86.

entails the recycling of the NEM separated at the back end into fresh fuel for use at the front end.

Today, the use of NEM in the front end of the fuel cycle, other than the NEM recycled from reprocessing, is not a major issue. Only one commercial power reactor in operation uses HEU as its fuel: the BN-600 fast-neutron breeder reactor in Russia. (A small number of smaller, experimental fast-neutron reactors also use HEU in their fuel.) The 20-30 percent enriched uranium fuel required by some breeder reactor designs is a considerably smaller proliferation risk than the 90 percent or 80 percent enriched material often used in research reactors, because of the large amount of HEU needed to constitute a critical mass at these lower enrichments.[66] Future fast-neutron reactors, if they are built and deployed, will likely use plutonium or U-233 recovered from spent fuel as their primary fuel, possibly mixed with other actinides and some of the fission products from spent fuel. (Such recycling is discussed in more detail below.) While there continue to be a few advocates for versions of the high-temperature gas-cooled reactor (HTGR) intended to breed U-233 from thorium using fuel enriched to weapon-grade or above),[67] it presently appears unlikely that major deployments of power reactors with material posing such a high

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[66] Such material would provide useful source material for further enrichment, reducing the amount of separative work required to produce bomb material. Very roughly, ten times less enrichment work is required, *if* the assay of U-235 in the tails is the same. Specifically, 19-21 SWU/Kg is required to produce 93 percent product using 20 percent feed, compared with 180 to 240 SWU/Kg for natural feed, depending on tails assay (0.4 to 0.2 percent). But the difference is much larger if those enriching 20 percent feed allow significant amounts of the U-235 to be lost to the tails: only 6.98 SWU/kg are required to produce 93 percent product using 20 percent feed with a tails assay of 15 percent. Much the same is true of typical LEU for a light-water reactor, however: 62 SWU/kg are required to produce 93 percent product using 4.5 percent feed, with a tails assay of 3 percent.

[67] In some concepts a reactor intended to make U-233 from thorium would contain fuel with very little U-238, so as to avoid making plutonium in the fuel. This is not essential, however. In an HTGR with 20 percent enriched uranium fuel mixed with thorium, plutonium production would be reduced to 30 kilograms per year for 1 gigawatt-electric of capacity operating at 90 percent capacity factor, and the U-233 produced would be isotopically denatured by the U-238 in the fuel. See, for example, Harold A. Feiveson, Frank von Hippel, and Robert H. Williams, "Fission Power: An Evolutionary Strategy," *Science* 203 (1979), pp. 330-337. Similarly, a variety of thorium-fuel designs are now being pursued (including for light-water reactors) in which thorium, U-238, and U-235 are all present in the fuel; the result, in some of these designs, is a modest extension of the amount of energy that can be generated from available uranium resources, combined with substantially lower production of substantially lower-quality plutonium in the spent fuel, than is typical for the spent fuel from light-water reactors operating with LEU fuel. A fast-reactor core is one that can sustain a chain reaction driven by fast neutrons, for which the enrichment requirement is the same as the minimum for a weapon, that is, around 20 percent U-235 or 12 percent U-233. (See Appendix A.)

proliferation hazard in their fresh fuel will occur in the foreseeable future.

The more substantial proliferation liability associated with the "front end" of the nuclear fuel cycle is not the direct use of NEM but the use of facilities that could be used to produce NEM. The same enrichment technologies and facilities used to make LEU for light-water reactors—the dominant reactor type in the world today—can be used to produce HEU for weapons. Indeed, an enrichment facility using gas centrifuges—the most cost-effective of the enrichment technologies commercially deployed today—can be reconfigured from LEU production to HEU production very quickly. The case of Iran has focused international attention on the possibility that a country could build such a facility while remaining within the NPT, then withdraw from the NPT and quickly begin producing HEU for nuclear weapons. Moreover, centrifuge enrichment plants large enough to produce a bomb's worth of HEU each year could potentially be small and difficult for either intelligence systems or inspectors to find. The recent revelation that a global black-market network centered on Pakistan's A.Q. Khan was peddling centrifuge technology to Iran, North Korea, Libya, and possibly others, and had initially acquired centrifuge designs and expertise illegally from Europe, highlights the proliferation danger posed by the spread of centrifuge technologies.

The use of NEM is a major issue at the "back end" of the nuclear fuel cycle. With currently available reprocessing and recycling approaches, plutonium or U-233 is completely separated from accompanying fission products before being incorporated into fresh fuel. As indicated above, the limited use of plutonium recycle in a small fraction of the world's current nuclear electricity generation has already led to significant plutonium stocks and flows in the civilian sector. If breeding and recycling were more heavily used, the associated stocks and flows of separated, directly weapon-usable material could become truly immense.[68] This poses challenges for international efforts to ensure against diversion and theft of any of this material, and as with enrichment plants, the possession of a reprocessing plant built while a party to the NPT would allow a state to withdraw from the NPT and rapidly begin separating NEM for weapons use.

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[68] A nuclear energy economy about 10 times larger than today's, say 3,500 GWE, and using NEM recycling for all operations, would entail flows of separated plutonium in excess of 3,500 tons per year.

Three general approaches could be used to avoid or reduce the proliferation liabilities and monitoring challenges associated with the use of NEM recycling and breeder reactors:

1. postponing, minimizing, or altogether avoiding the use of breeding and recycling;[69]
2. attempting to develop advanced breeder-reactor fuel cycles in which the recycled plutonium or U-233 would never be completely separated from fission products (meaning that these materials would only become weapon usable if they underwent an additional reprocessing step); and
3. utilizing the concept of carefully guarded and internationally owned, managed, and monitored nuclear energy complexes, in which enrichment, fuel fabrication, power generation, and fuel reprocessing would all take place within a single site from which no NEM would ever emerge.

Clearly, combinations of these approaches can be envisioned, including postponing the use of breeding and recycling until they are economically beneficial and further development makes these technologies more proliferation resistant and/or until the internationalized nuclear-energy-complex approach is accepted as a requirement for their use.

History, Status, and Transparency Issues

After an extended internal and external debate about the benefits versus the liabilities of plutonium recycle and breeder reactors, the Ford Administration announced in 1976—and the Carter Administration subsequently strongly reiterated—that it was U.S. policy to refrain indefinitely from fuel reprocessing for commercial recycle of plutonium and from deployment of breeder reactors for electric power production and, further, that the United States would try to persuade other countries to refrain from commercial

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[69] Postponing or avoiding recycling has the liability of making the requirements for uranium and for uranium enrichment services larger than they would be if recycling were used. How soon and to what extent the liability of increased uranium needs would become a significant one depends both on the rate of growth of nuclear electricity generation worldwide and on the extent to which relatively low-cost uranium resources prove extendable by some combination of new discoveries and advanced technologies for exploiting low-grade uranium ores, including ordinary granite (10-20 parts per million U) and sea water (3 parts per billion U). The increased enrichment requirement associated with postponing or avoiding plutonium recycle could aggravate the proliferation risks associated with enrichment, unless it is successfully internationalized. See, e.g., Richard L. Garwin and Georges Charpak, *Megawatts and Megatons: The Future of Nuclear Power and Nuclear Weapons* (Chicago: The University of Chicago Press, 2002). and John Deutch, Ernie Moniz, et al., *The Future of Nuclear Power: An Interdisciplinary MIT Study* (Cambridge, MA: Massachusetts Institute of Technology, 2003). Available as of January 2005, at: http://web.mit.edu/nuclearpower/.

use of these technologies. The rationale for this position was precisely the desire to minimize commercial stocks and flows of plutonium, on nonproliferation grounds; furthermore, analyses indicated that, given the low cost availability of uranium, there would be no economic benefit for the foreseeable future from recycling or breeding in comparison with once-through use of LEU fuel in existing commercial reactor types.[70]

This policy was controversial both within the United States, where many in the nuclear energy industry felt that moving to plutonium recycle and breeding was the technically logical progression for nuclear energy technology and should be pursued, and elsewhere, particularly in France, Belgium, Germany, Switzerland, the United Kingdom, Japan, and the Soviet Union, which either were starting to practice breeding and/or recycling or were committed to doing so in the near future. A concerted effort by the Carter Administration to develop international support for a moratorium on commercial recycling of plutonium and breeder reactors failed to rally hoped-for support. Early in the Reagan Administration, the Carter policy was reversed, although this had essentially no practical effect because U.S. electric utilities had by then concluded that these technologies were indeed uneconomic given prevailing and foreseeable uranium prices. The continuing *de facto* U.S. moratorium on reprocessing and commercialization of breeder reactors initially had no discernible effect on the enthusiasm for these technologies, particularly in France, Japan, and the Soviet Union.

In the 1990s the Clinton Administration restored restraint on reprocessing and breeding in nuclear energy systems as stated U.S. policy, but retreated from the Carter version by saying that the United States would not actively discourage its allies from using these technologies. The May 2001 national energy policy document of the George W. Bush Administration called for the United States to continue to "discourage the accumulation of separated plutonium" in civil nuclear fuel cycles, while proposing pursuit of "fuel conditioning" technologies such as pyroprocessing that could reduce waste streams and increase proliferation resistance;[71] the

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[70] Spurgeon M. Keeny Jr. et al., *Nuclear Power Issues and Choices*, Report of the Nuclear Energy Policy Study Group, Ford Foundation/MITRE Corp. (Cambridge, MA: Ballinger Publishing Company, 1977).

[71] Pyroprocessing, also know as molten salt electrochemical processing, is a material purification method that can be used to purify plutonium. "It involves anodization (oxidation) of a metal into a molten salt electrolyte and then reduction at a cathode to yield a more (highly) purified form." See

Bush document also proposed collaborative research with other countries on approaches to reprocessing superior to those available today.[72]

At this writing, the United Kingdom and France are continuing commercial reprocessing of plutonium not only from their own spent fuel but also under commercial contracts with Japan, Germany, Belgium, and Switzerland, among others. Few additional foreign reprocessing contracts are available, however. The United Kingdom has announced that its Thermal Oxide Reprocessing Plant (THORP) will close in 2012; its Magnox reprocessing plant will shut down when the aging Magnox reactors are closed.[73] French reprocessing is currently planned to continue, focusing on reprocessing domestic spent fuel. Serious technical problems, however, are plaguing the French breeder program.

While reprocessing also continues in Russia, with the collapse of the Soviet Union, Russia drastically slowed its formerly ambitious breeder reactor program. And at this writing, the one potential medium-size "breeder," the BN-600, is actually operating as a "burner" reactor and work on a larger one is proceeding very slowly. In addition, soaring cost estimates are beginning to generate internal debate in Japan about the wisdom of that country's previous strong commitment to reprocessing and breeding and Germany has lost interest in both breeding and recycling, en route to questioning the future of nuclear energy in Germany altogether.

New research and development initiatives such as the U.S.-led "Generation IV" effort have focused renewed attention on advanced breeder designs, but most of these focus on systems where the recycled plutonium or U-233 always remains mixed with other actinides and/or some fission products, to increase proliferation resistance. Still, no international consensus has emerged on whether avoiding or minimizing commercial traffic in separated plutonium would be an essential element of any suitably compre-

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National Research Council *Electrometallurgical Techniques for DOE Spent Fuel Treatment: Final Report* (Washington, DC: National Academies Press, 2000), p. 18.

[72] The White House, Report of the National Energy Policy Development Group ("Cheney Commission"), *National Energy Policy*, (Washington, DC: U.S. Government Printing Office, May 2001).

[73] For BNFL's plan to close the Magnox reprocessing plant by 2012, see, for example, Pearl Marshall, "BNFL's Magnox Reprocessing Plant Will Need to Double Throughput," *Nuclear Fuel,* (March 31, 2003); for BNFL's confirmation that contracted THORP business extends only to 2010, see Pearl Marshall, "BNFL Offers Conflicting Figures on Size of THORP Order Book," *Nuclear Fuel* (September 1, 2003).

hensive approach to nuclear arms control, nuclear nonproliferation, and nuclear counterterrorism.

Considerations and Options Looking Ahead

There is no question that the use of NEM and technologies for producing NEM in civil nuclear energy systems greatly increases the problems associated with the control and monitoring of NEM and thereby increases the risk of nuclear proliferation and nuclear terrorism, as well as the potential for future breakout in any future regime that entails much smaller nuclear arsenals. Indeed, the challenges posed by unrestrained use of NEM in civil nuclear energy to adequate defenses against nuclear proliferation and nuclear terrorism and to adequate verification of a more stringent and comprehensive arms control regime, were one desired, have been asserted by some to be virtually insurmountable.[74]

We believe that it is therefore important to revisit the question of whether and how the use of NEM in civil nuclear energy should be restrained, both for immediate purposes of nuclear nonproliferation and nuclear terrorism prevention and for the longer-term possibility of a more comprehensive nuclear arms limitation regime. Since the Ford and Carter administrations' announcements in the mid-1970s that the United States would refrain from commercial reprocessing of spent fuel, plutonium recycle, and deployment of breeder reactors, the proliferation and terrorism dangers from reprocessing and recycle of NEM have become even clearer than they were then. It has also become clearer that pushing forward with breeding and/or reprocessing/recycle any time soon will incur significant economic penalties, and greatly increased public controversy over the future of nuclear energy generation, thus reducing rather than enhancing the prospects for an expanded contribution from nuclear energy to meeting society's pressing energy needs.[75]

In these circumstances, we conclude that the United States should consider what steps could be taken to implement the stated Bush Administration policy of continuing to discourage the accumulation of separated plutonium in civil fuel cycles. One approach

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[74] See,. e.g., Christopher E. Paine, Thomas B. Cochran, and Robert S. Norris, "Technical Realities Confronting Transition to a Nuclear-Weapon-Free World" and "Current Political Realities Facing the Transition to a Nuclear-Weapon-Free World," *Background Papers for the Canberra Commission on the Elimination of Nuclear Weapons*, Government of Australia, August 1996, pp. 109-133.

[75] Richard L. Garwin and Georges Charpak, *Megawatts and Megatons: The Future of Nuclear Power and Nuclear Weapons* (Chicago: The University of Chicago Press, 2002).

was envisioned by President Bush in his February 2004 speech on nuclear nonproliferation, which called for ceasing the export of enrichment and reprocessing technologies to states that did not already possess them, and offering credible guarantees of fuel cycle supply to any state that agreed not to have enrichment and reprocessing facilities of its own.[76]

Measures that could be considered that would go beyond those called for by President Bush would include the U.S. government refraining from, and prohibiting U.S. firms from engaging in, any form of multilateral nuclear-energy cooperation or assistance likely to contribute to advancing commercial breeding or commercial reprocessing in any country. The U.S. effort could also press, and where practicable offer incentives to, Russia, France, and Japan to declare moratoria on civil reprocessing, with some of the plutonium fuel fabrication capacity that would otherwise be made surplus by this step then being turned to the task of fabricating fuel from surplus civilian and weapon plutonium (see the discussion of "disposition" below).

Specifically, an agreement with Russia on a joint 20-year moratorium on further civil plutonium separation coupled with a joint R&D program on more proliferation-resistant approaches to reprocessing and recycling could be a major contribution in buying time to resolve this problem. Such an agreement was almost completed at the end of the Clinton Administration. Under such an approach, research on advanced approaches to breeding and reprocessing that might be able to reduce the vulnerability of such operations to breakout (of nuclear weapon states from agreed limits) and to proliferation and theft—and that might be able to lower costs, improve safety, or bring waste management advantages—could be continued. For at least the next two decades, however, such research might be constrained not to progress to large-scale development (which would entail processing and handling significant quantities of NEM), and it might be confined as far as possible to nuclear weapon states, so as to minimize diffusion of exper-

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[76] President George W. Bush, remarks to the National Defense University, February 11, 2004, available as of January 2005, at: http://www.whitehouse.gov/news/releases/2004/02/20040211-4.html. For a useful discussion of how such fuel cycle guarantees might be implemented, from some one with experience both at the IAEA and in leading major commercial fuel cycle activities, see Pierre Goldschmidt, "The Proliferation Challenge of the Nuclear Fuel Cycle in Non-Nuclear Weapon States," remarks to the Institut Français des Relations Internationales, April 26, 2004, available as of January 2005, at:
http://www.iaea.org/NewsCenter/Statements/DDGs/2004/goldschmidt26042004.html.

tise and experience with reprocessing and plutonium-handling technologies that would be of value to potential proliferators.[77] The rationale for not proceeding to large-scale development for at least two decades includes *both* the high desirability of minimizing reprocessing-linked proliferation and terrorism hazards in this critical time frame *and* the near certainty that the availability of relatively low-cost uranium would prove sufficient to support any plausible rate of growth of nuclear energy worldwide through at least 2050.

As for full-scale development and deployment of civilian nuclear reactor types that require the use of HEU in their fresh fuel, this too could be postponed unless and until there is a strong case that such reactors and their fuel cycles can offer a combination of economic, safety, waste management, and back-end-of-fuel-cycle nonproliferation advantages sufficient to offset the nuclear proliferation, nuclear terrorism, arms limitation breakout, and NEM-monitoring liabilities of the “front end” use of HEU.

Serious consideration should also be given to a more farreaching solution proposed in the past and recently advanced again by IAEA Director General Mohamed ElBaradei to place all production of NEM under direct international control.[78] This would place all uranium enrichment as well as all plutonium separation and plutonium fuel fabrication (whether this uses reprocessed civil plutonium or surplus military plutonium) under multilateral management and control, not just under IAEA safeguards. This would ensure not only full transparency and accountability but also that physical protection meets a high and internationally agreed standard, and that individual states could not convert their facilities to military production by withdrawing from the NPT. Under this arrangement participants would be guaranteed access to fuel containing LEU, which would be returned to the international entity after irradiation.

If the principle could be established that there would be no new facilities capable of producing NEM in any state, including the nuclear weapon states, except under international control, this would

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[77] See John Deutch, Ernie Moniz, et al., *The Future of Nuclear Power: An Interdisciplinary MIT Study* (Cambridge, MA: Massachusetts Institute of Technology, 2003). Available as of January 2005, at: http://web.mit.edu/nuclearpower/. The authors argue that a re-evaluation in 2020 would come in ample time to allow for adequate development and deployment of breeding and reprocessing options by 2050, if that seemed appropriate.

[78] Mohamed ElBaradei, “Toward a Safer World,” *The Economist* (October 16, 2003), p. 47.

be a major step toward eliminating a large weakness in the nonproliferation regime, which currently allows participants to come right to the edge of a nuclear weapon capability while legally remaining within the regime.

In short, constraints could be introduced on utilization of NEM in the fuel cycle at no economic sacrifice for some time to come while efforts are pursued to deal with the threats these developments entail. If agreement cannot be reached on implementing these constraints, MPC&A procedures could be introduced to ameliorate the threat—at significantly increased costs and uncertainty as to effectiveness.

Other Actions to Consolidate NEM at Fewer Sites

Reducing the number of, or eliminating entirely, research reactors that use HEU and postponing, minimizing, or avoiding nuclear energy technologies that entail the use of HEU and/or separated plutonium at dispersed sites are two ways to reduce the number of locations where these materials must be monitored and guarded, as well as to reduce the amount of transportation of the materials among sites. Reducing the number of R&D facilities, civil and military, that work with appreciable quantities of either HEU or plutonium is another way to do this.

Some of these actions would reduce not only the number of sites but the total quantity of NEM as well. But it is worth emphasizing that actions that merely consolidate NEM in fewer sites without reducing the total quantity (as nuclear energy complexes with large numbers of reactors would do) are also worthwhile. Consolidating the national inventories of civil and military NEM in fewer (and better protected and monitored) facilities is the most straightforward example of this. Consolidating civil NEM across countries, into multinationally monitored NEM "banks," would be a more ambitious and highly worthwhile approach.

Consolidation brings benefits for NEM security as well as for NEM monitoring because it is technically easier and more economical to thoroughly protect and monitor a few facilities, each with a lot of material, than to protect and monitor many facilities, each with much smaller amounts. In addition, insofar as most corrupt guards or officials and criminal groups probably would not aspire to steal more than a few tens or at most a few hundreds of kilograms of NEM in one attempt (because the difficulty of transportation would complicate the task and increase the chance of being apprehended), the theft risk does not increase in proportion to the amount of material stored in one place.[79]

History, Status, and Transparency Issues

Both in the United States and in Russia, the post-Cold War downsizing of the two countries' nuclear weapon production complexes has led to a reduction of the number of facilities processing and storing military NEM, though much remains to be done in both cases. In Russia, for example, scores of former nuclear weapon storage sites have been closed down, two of the four weapon assembly and disassembly facilities have been closed, one of the two facilities for processing NEM into weapon components has been closed, most of the facilities that once stored fresh HEU naval fuel have been closed (and the others equipped with effective security and accounting systems), the enrichment plants no longer produce HEU, and 10 of the 13 plutonium production reactors (all of which also used 90 percent enriched HEU "spike" fuel) have been closed. Currently, plutonium from the dismantling of surplus nuclear weapons (which is taking place at four sites) is to be shipped to the new storage facility at Mayak, which at this writing is completed but not yet in operation. HEU from dismantled Russian nuclear weapons is being stored at the four dismantling sites, and is then transported thousands of kilometers for processing to LEU as part of the U.S.-Russian HEU Purchase Agreement. HEU for fueling nuclear-powered icebreakers and naval vessels continues to be fabricated, shipped over thousands of kilometers, and used in quantities comparable to or larger than all HEU used by research reactors worldwide.

In the United States, scores of buildings that once held NEM have had all of the NEM removed, as has the Rocky Flats site, where plutonium weapons components were fabricated (resulting in substantial savings in annual security costs). Currently, all dismantling takes place at the Pantex facility near Amarillo, Texas, and the resulting plutonium is stored in bunkers at the same site. The HEU from dismantled U.S. nuclear weapons is stored at Oak Ridge. Excess HEU from there and from other sites is being shipped to processing facilities for blending to LEU. Very large quantities of HEU exist, however, which have been reserved for

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[79] A disturbing example of the problem as an "inside" job involves the incident where Alexander Tyulyakov, Deputy Director of Atomflot, was found to have smuggled HEU off site. David Filipov, "Conviction Underscores Threat of Nuclear Theft: Russian Fleet Official Stored, Tried to Sell Radioactive Material," *The Boston Globe*, November 26, 2003, p. A8.

use as naval fuel, rather than being declared excess. As in Russia, this material is processed, fabricated, shipped, and used on a very large scale every year.

Elsewhere in the world, the pace of consolidating NEM sites has been quite slow. With the successes in removing Soviet-supplied HEU from the former Yugoslavia, Romania, Bulgaria, and Libya in 2002-2004, and the announcement of the Global Threat Reduction Initiative (GTRI) in 2004, it is to be hoped that progress will accelerate. It will be important for the implementers of the GTRI to ensure that all nuclear materials that pose substantial proliferation threats are covered, and not just HEU research reactor fuel. As just one example, a research center at Kharkov, in Ukraine, holds a substantial quantity of 90 percent enriched HEU in the form of oxide powder, though it has no research reactor.[80]

Considerations and Options Looking Ahead

We believe that substantial further consolidation of NEM in the nuclear weapon states would be desirable, particularly in Russia. Many Russian facilities still have NEM in many different buildings on-site, though in the context of U.S.-Russian MPC&A cooperation, work is underway to consolidate the materials at these sites into central storage facilities. Only very modest progress is being made in removing materials entirely from sites within Russia. To accelerate that effort, the United States could work with the Russian government to:

- convince the Russian government to draw up a plan for consolidation of the number of buildings and sites where NEM and nuclear weapons exist, offering assistance in preparing and implementing such a plan (as has been discussed between U.S. and Russian experts);
- change the incentives that currently make most Russian sites eager to retain their NEM, and to structure a set of incentives to encourage facilities to give up their NEM;
- begin converting HEU-fueled research reactors within Russia (not only Soviet-supplied facilities outside of Russia) to use LEU fuels, including critical assemblies and pulse power facilities with significant quantities of HEU; and

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[80] Joseph Cirincione et al., *Deadly Arsenals: Tracking Weapons of Mass Destruction* (Washington, DC: Carnegie Endowment for International Peace, 2002), p. 332.

- develop and implement LEU fuels for Russia's nuclear-powered icebreakers and ultimately for naval vessels as well.

The partial measures that have been taken to date under this heading mainly reflect a post-Cold War interest in reducing the vulnerability of NEM stocks to theft by criminals, terrorists, and agents of proliferant states. If a more comprehensive approach to nuclear arms control were adopted encompassing NEM, an expanded set of measures for reducing vulnerable stocks and flows of those materials would become increasingly important.

Removing NEM entirely from the most vulnerable sites is generally a superior strategy to trying to upgrade security for it, in place, at its current locations. It is germane here that some sites have little prospect of the continuing revenue streams that would be needed to maintain adequate security over the long run, even assuming that initial assistance is provided to put a suitable security system in place. Some vulnerable facilities are in locations that are inherently difficult to secure, either because the environment does not allow for an adequate security infrastructure or because the location entails the possibility of threats too big for any plausible security system to handle, such as civil war.

Cutoff of Production of NEM for Weapons

In a world awash in NEM, we believe that a permanent ban on the production of NEM for weapons could only be a benefit for nuclear theft prevention, nonproliferation, and arms control. It could also ultimately ease the overall problem of monitoring a more comprehensive nuclear arms limitation regime, if one materialized, even as it created some specific new challenges in connection with monitoring the production halt itself.

Decisions to halt production of NEM for weapons have been made unilaterally by some states in the past and may be made by others in this way in the future; such decisions may also be part of a multilateral or international agreement to refrain from such production. At present, all non-nuclear weapon states party to the NPT are subject to a verified ban on the production of NEM for weapons. The five *de jure* nuclear weapon states party to the NPT (the United States, Russia, the United Kingdom, France, and China) are not covered by this ban, but they are no longer producing NEM for weapons. There is, however, no formal commitment by the *de jure* nuclear weapon states to make these halts permanent. Thus the utility of such an agreement depends on the willingness of the nonmember states of the NPT to participate without having to join the NPT. In sum, all states are currently either covered by a ban on producing NEM for weapons or are voluntarily abiding by it except the *de facto* nuclear weapon states (India, Israel, and Pakistan), which are not members of the NPT, and North Korea since its recent withdrawal from the NPT.

Unilateral Initiatives

To the extent that production halts of NEM for weapons are unilateral and not subject to verification through bilateral, multilateral, or IAEA inspections, confirmation that declared cutoffs are in fact being honored would depend primarily on information gathered by National Technical Means, which are discussed in Chapter 4. In general, large scale plutonium-production reactors and fuel reprocessing plants for separating plutonium from the fuel of such reactors are relatively conspicuous undertakings. Their existence would be difficult to conceal over any extended period of time. Without inspections, however, it would be difficult if not impossible, to determine whether any of the plutonium from reprocessing plants was destined for weapons. Similarly, gaseous diffusion uranium enrichment plants would be very difficult to conceal for an extended period of time, but the existence and operation of small gas centrifuge or laser enrichment plants would be more difficult to detect—and once detected, it would be difficult to confirm without inspection whether such plants were operating or not. Without inspections, moreover, determination of whether the output of an operating enrichment plant was LEU or HEU would also be difficult if not impossible, as would be the determination of whether any HEU produced was destined for weapons, tritium production reactors, naval reactors, research reactors, or civil power reactors of types that use HEU.

U.S.-funded efforts to end the production of separated plutonium from the three remaining Russian plutonium producing reactors in Siberia began with attempts to arrange alternate sources of heat and power for their regions so that the reactors could be shut down, then shifted to a focus on modifying the fuel for the reactors so that it would produce little plutonium and would not need to be reprocessed for technical reasons as is currently the case, and now have shifted back to replacing the reactors with other sources of heat and electricity. Although the United States and Russia originally agreed in 1994 that the reactors would be shut down by 2000, they are now expected to operate until some time between 2008 and 2011, with the separated plutonium subject to U S. monitoring to assure that it has not been diverted from storage to weapons.[81] During 2003, the United States let contracts to the U.S. firms that are to oversee construction of the replacement power supplies, and reached agreement with Russia on access and other implementation matters.[82]

Fissile Material Cutoff Treaty

Since 1978 the U.N. General Assembly has supported resolutions calling for a stand-alone international convention calling for a cutoff of production of NEM for weapons by all states. But precisely what would be prohibited and what would be permitted under such a cutoff, and what would be monitored in order to verify it, as well as whether such a pact should be linked to other arms control issues, remain contentious questions.

The prospects for an international Fissile Material Cutoff Treaty (FMCT) formally prohibiting the production of NEM for weapons by all states appeared to improve when in 1993 the Clinton Administration reversed the U.S. position from opposition to active support for a comprehensive international cutoff agreement, and a resolution adopted by consensus in the U.N. General Assembly called for negotiation of a "non-discriminatory multilateral and internationally and effectively verifiable treaty banning the production of fissile material for nuclear weapons or other nuclear explosive devices."[83] In 1995, following consultations with states participating in the Geneva-based Conference on Disarmament (CD), the conference agreed to begin negotiations on an FMCT. But that mandate for negotiation expired with the end of that year's conference session and has been renewed only once since then, for three weeks in 1998. Despite repeated calls from the UN General Assembly and NPT review conferences to pursue a cutoff treaty, negotiations have not resumed because the CD operates on the basis of consensus and a few states have been able to block any further negotiations on a cutoff because of disagreements about its scope

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[81] U.S. Department of Energy, *FY2004 Detailed Budget Justification–Defense Nuclear Nonproliferation* (Washington, DC: Department of Energy, February 2003), p. 713.

[82] See, for example, the brief discussion on the official Web site of the Department of Energy's Eliminating Weapon-Grade Plutonium Production (EWGP) program, available as of January 2005, at: http://www.nnsa.doe.gov/na-20/ewgpp.shtml.

[83] United Nations General Assembly, *Prohibition of the Production of Fissile Materials for Weapons or Other Nuclear Explosive Devices,* UNGA 48/75L, December 16, 1993. Available as of January 2005, at: http://www.acronym.org.uk/fissban/fmctdesc.htm#one.

and purpose and a desire to link it to consideration of other issues, such as a ban on the weaponization of space.[84]

In 2003 China softened its position linking the start of negotiations to parallel discussions on preventing an arms race in outer space, but at the same time the Bush Administration launched an extended review of U.S. policy supporting a fissile material cutoff. In July 2004 Jackie Sanders, the U.S. Ambassador to the CD, announced that the review "raised serious concerns that realistic, effective verification of an FMCT is not achievable."[85] A State Department policy paper explained the change in the U.S. position further: "Effective verification of an FMCT would require an inspection regime so extensive that it could compromise key signatories' core national security interests and so costly that many countries will be hesitant to accept it. Moreover, we have concluded that, even with extensive verification measures, we will not have high confidence in our ability to monitor compliance with an FMCT."[86]

Given the fact that there is now a *de jure* cutoff of NEM production for weapons for all non-nuclear weapons states party to the NPT and a *de facto* moratorium on such production by the five nuclear weapon states party to that treaty, the immediate impact of a comprehensive FMCT would be on the four nonmembers of the NPT (India, Israel, Pakistan, and North Korea), which are still, in fact, producing NEM for weapons. The issue of resumption of the FMCT negotiations and in particular the problem of inclusion of these four states is not a technical but a political problem beyond the scope of this study.

Considerations and Options Looking Ahead

We judge that immediately available steps that the United States might take toward a more complete and durable halt to production of NEM for weapons—and toward transparency and verification measures adequate to support this—include the following:

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[84] See, for example, U.S. Department of State, *Fissile Material Cutoff Treaty* (Washington, DC: Department of State, June 29, 1999). Available as of January 2005, at: http://usinfo.state.gov/topical/pol/arms/stories/fsmbckgr.htm and Hui Zhang, "A Chinese View on a Fissile Material Cut-off Treaty," *Journal of Nuclear Materials Management* 30 (4) (2002).

[85] "U.S. Proposals to the Conference on Disarmament," Jackie W. Sanders; Permanent Representative to the Conference on Disarmament and Special Representative of the President for the Nonproliferation of Nuclear Weapons. Remarks to Conference on Disarmament Geneva, Switzerland July 29, 2004. Available as of January 2005, at: http://www.state.gov/t/ac/rls/rm/2004/34929.htm.

[86] "Fissile Material Cut-off Treaty Policy," Department of State Press Release, July 29, 2004.

- Completion of the program to replace the heat and power from Russia's three remaining plutonium production reactors so that they can be shut down;
- Agreement and implementation of monitoring measures to confirm U.S. and Russian statements that these two countries are no longer producing HEU;
- Conduct of joint U.S.-Russian demonstrations to verify that older reprocessing plants are not separating Pu for weapons; and
- Pursuit a truly international moratorium on the production of NEM for weapons as a precursor to a verifiable international treaty banning such production permanently.

The verification measures for a FMCT would clearly need to include declarations for all reprocessing and enrichment facilities, whether currently operational or not, and for all other facilities that store or process NEM subject to the treaty. There would presumably also be a need for declarations of all facilities that store or handle preexisting NEM not addressed by the cutoff, in order to deal with the problem of discriminating preexisting material from new production.[87]

It would seem simplest for the monitoring procedures under an FMCT to be coincident, in the case of non-nuclear weapon states, with those currently applied by the IAEA under the Additional Protocol, and for new or amended agreements with nuclear weapon states to adhere as closely as possible to the same approaches, with only such modifications as required to address special circumstances of those states such as dual-purpose facilities and facilities not designed to accommodate standard IAEA procedures.[88]

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[87] See, e.g., Victor Bragin, John Carlson, and John Hill, "Verifying a Fissile-Material Production Cut-Off Treaty," *The Nonproliferation Review*, Fall 1998, pp. 97-107; and Annette Schaper, "Monitoring and Verifying the Storage and Disposition of Fissile Materials and the Closure of Nuclear Facilities," in Nicholas Zarimpas, ed., *Transparency in Nuclear Warheads and Materials* (New York: Oxford University Press and Stockholm International Peace Research Institute, 2003), pp. 206-228.

[88] The current IAEA procedures for non-nuclear weapon state parties to the NPT are described under INFCIRC/153 and the Model Safeguards Protocol (INFCIRC/540); the parameters of the more limited, facility-specific safeguards agreements that have been negotiated with nuclear weapon states are described in INFCIRC/66. See IAEA, INFCIRC/66, revision 2: *The Agency's Safeguards System (1965, As Provisionally Extended In 1966 And 1968)* (Vienna: International Atomic Energy Agency, September 1968); and IAEA, INFCIRC/153 (corrected): *The Structure And Content Of Agreements Between The Agency And States Required In Connection With The Treaty On The Non-Proliferation Of Nuclear Weapons* (Vienna: International Atomic Energy Agency, June 1972); and IAEA,

Technical issues that will need to be addressed in a monitoring system for an FMCT include how to monitor older, nuclear-weapon-state reprocessing and enrichment plants and how to verify quantities and composition of naval fuel using HEU produced after an FMCT is concluded (assuming that such production has not been banned) without compromising classified information on fuel composition and design. These are manageable problems on which the United States and Russia could begin working together, and with the IAEA, on how best to solve them. By far the most difficult issue, however, will be the political problem of including the four non-NPT members (India, Israel, Pakistan, and North Korea) in such an agreement, since it would primarily affect them at this time.

Final Disposition of NEM

Final disposition covers reducing surplus stocks of NEM by putting them in locations from which they would be very difficult or impossible to recover, or by mixing them with contaminants that make them unusable for weaponry and from which they can only be separated again with great difficulty, or by a combination of these means. Final disposition reduces NEM stocks over time to below what they would otherwise be and eases the task of monitoring what remains. But the transport and processing of NEM associated with accomplishing final disposition will in themselves create opportunities for theft or diversion and difficulties for monitoring that may be more serious during the period when disposition is taking place than those associated with simple guarded storage of the NEM, and they would require intense attention to ensuring that effective security and monitoring measures are in place throughout the process.

Concepts and Technologies for Final Disposition

A study conducted by the Committee on International Security and Arms Control (CISAC) from 1992 to 1995 at the request of the U.S. government addressed the possibilities for disposition of sur-

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INFCIRC/540 - *Model Protocol Additional To The Agreement(S) Between State(S) And The International Atomic Energy Agency For The Application Of Safeguards* (Vienna: International Atomic Energy Agency, October 1993); all available as of January 2005, at: http://www.iaea.org/Publications/Documents/Infcircs/.

plus military NEM in considerable detail.[89] The CISAC reports recommended that the United States and Russia pursue long-term disposition options that (a) minimize the time during which this material 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 HEU would be as difficult to recover for weapons use as from commercial LEU, and the plutonium would be as difficult to recover for weapons use as the much larger and growing quantity of plutonium in commercial spent fuel (the "spent fuel standard"); and (d) meet high standards of protection for public and worker health and the environment.

Disposition of HEU

In the case of HEU, achieving these goals is technically straightforward. Highly enriched uranium can be blended with natural uranium—or with the depleted-in-U-235 "tails" from previous uranium enrichment or very low enriched uranium for technical reasons—to produce proliferation-resistant LEU, which is a valuable commercial fuel. This was the basis of the "HEU deal" concluded between the United States and Russia in the early 1990s, as well as the U.S. decision to undertake a similar blending process for most of its own stockpile of excess HEU.

At two of the three Russian facilities where the material is blended down under the HEU Purchase Agreement, the United States conducts continuous automated monitoring of the three pipes in the Y joint where the blending occurs; one carrying 90 percent enriched uranium hexafluoride, one carrying 1.5 percent enriched uranium hexafluoride used to blend down the HEU, and the pipe carrying the merged blend, with about 4 percent enrichment. (Slightly enriched material rather than natural or depleted uranium is being used for the blending to further dilute undesirable isotopes in the HEU, such as U-234 and U-236.) Installation of monitoring at the third facility was scheduled for late 2004.

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[89] Committee on International Security and Arms Control, *Management and Disposition of Excess Weapons Plutonium* (Washington, DC: National Academy Press, 1994) and Committee on International Security and Arms Control, Panel on Reactor-Related Options, *Management and Disposition of Excess Weapons Plutonium: Reactor-Related Options* (Washington, DC: National Academy Press, 1995). See also the important precursor work, Frans Berkhout, Anatoli Diakov, Harold Feiveson, Helen Hunt, Edwin Lyman, Marvin Miller, and Frank von Hippel, "Disposition of Separated Plutonium," *Science and Global Security* 3, 1993.

In order to establish some level of confidence that the HEU indeed comes from dismantled weapons as required and not reserve stocks of HEU, the United States is allowed several visits each year to the facilities where HEU metal weapon components are cut into metal shavings and converted to oxide. During these visits, the United States has the opportunity to observe rough measurements of the U-235 enrichment of the weapons components in containers and of the resulting metal shavings and oxide in containers, to tag and seal containers being readied for shipment to the blending facility, and to review records of these activities that take place when U.S. inspectors are not present. Similarly, Russian inspectors have the right to conduct monitoring at the U.S. enrichment facility where the LEU is received and processed and at the U.S. fabrication facilities where the material is fabricated into reactor fuel.[90]

Disposition of Plutonium

Disposition of plutonium poses much more difficult technical challenges. Because all isotopes of plutonium are weapons usable, plutonium cannot be blended isotopically to an adequately proliferation resistant form in the way that HEU can. Given the current worldwide supply of cheap uranium and the high cost of fabricating reactor fuel that contains plutonium, the use of even “free” plutonium as fuel in reactors is uneconomic now and likely to remain so for at least the next few decades. Thus, all of the options for disposition of surplus weapon plutonium, including those that use the plutonium as fuel in civilian reactors, will require substantial investments. There is no disposition option that will “make money.”

The 1992-1995 CISAC study examined all plausible identified options for plutonium disposition, including placing the plutonium at the bottom of deep (several kilometers) boreholes in solid rock, burying it in special zones on the deep ocean floor, and launching it into the sun or out of the solar system on rockets. The study concluded that while all plutonium disposition options have drawbacks, the two least problematic options for achieving the four aims listed above for disposition of NEM are:

1. fabrication of the plutonium into mixed oxide fuel (a mixture of plutonium dioxide and uranium dioxide, termed

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[90] See, for example, Matthew Bunn, “Highly Enriched Uranium Transparency,” Monitoring Stockpiles. Available as of January 2005, at: http://www.nti.org/e_research/cnwm/monitoring/uranium.asp and references cited therein. The official Web Site of the HEU Transparency Implementation program is available as of January 2005, at: http://www.nnsa.doe.gov/na-20/heu_trans.shtml.

"MOX") for use on a "once through" basis in a limited number of civilian power reactors of currently operating types (albeit possibly with some modifications to increase the achievable plutonium loading per reactor in order to speed up the process or reduce the number of reactors needed); or

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

The residual (unfissioned) plutonium in the MOX approach would be part of the radioactive wastes similar to what would have been produced in any case from energy generation in the civilian power reactors chosen for the plutonium disposition mission, and the plutonium would remain a part of these wastes through whatever intermediate and final storage steps society choose for them.[91] In the vitrification approach, the plutonium-bearing logs would likewise become part of a radioactive waste management burden that would exist in any case in the form of glass logs serving to immobilize previously generated fission products. Either of these options or a combination of them would be appropriate to achieve final disposition of plutonium. The 1995 CISAC report recommended that both options be developed expeditiously in parallel.

History, Status, and TransparencyIissues

The implementation of the U.S.-Russian HEU deal described in Chapter 1 was slowed and ultimately even imperiled by a number of management decisions, most importantly the decision in the mid-1990s to privatize the theretofore government-operated uranium-enrichment industry in the United States. Once the U.S. Enrichment Corporation (later renamed USEC), which had been the "executive agent" for the HEU deal on the U.S. side from the beginning, became private the resulting tension between profit mo-

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[91] It is worth noting that because MOX is typically only used in one third of the reactor core, with the rest being LEU, and because both the LEU and the MOX contain large quantities of U-238, nearly as much plutonium is produced when MOX is burned in such an arrangement as is consumed. But the produced plutonium is in spent fuel, not in separated forms much easier to use in weapons. And if the same reactor core had operated without MOX, with an all-LEU core, the net plutonium generation would have been even higher.

tive and national security goals—the former favoring implementation of the deal on terms that would maximize returns to USEC's stockholders and the latter favoring implementation on terms that would maximize the rate of down blending and transfer of Russian HEU—led to a series of delays, disagreements, and renegotiations.[92]

Despite these problems, by January 2005 Russia had blended down more than 230 tons of HEU to LEU under this program. The process is now proceeding at an annual rate of about 30 tons of HEU. The program is scheduled to end in 2013, when the 500 tons of HEU covered by the original deal will have all been blended down to LEU. This figure, which represents about half of the total Russian stockpile of HEU inside and outside of weapons, is equivalent to as many as 20,000 to 25,000 nuclear weapons, depending on design.[93]

Progress toward final disposition of excess weapons plutonium has been much slower. Following the CISAC recommendations and reviews by U.S. governmental and bilateral U.S.-Russian panels, the two options were embraced by the official U.S. announcement of the dual-track approach for plutonium disposition in December 1996. These options had been endorsed earlier at the international level at the U.S.-Russian summit in Moscow in April 1996, and at a subsequent international experts meeting in the fall of 1996. Currently, however, the immobilization option has been largely abandoned and the pursuit of the MOX option has been seriously slowed by legal and economic problems. So far, none of the weapons plutonium declared excess has been disposed of.

Both the United States and Russia have some but not all of the facilities they would need to undertake plutonium disposition. For the reactor option, new plutonium fuel fabrication facilities and plants for converting plutonium pits to oxide would be needed, and this would be the limiting requirement in both time and cost for

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[92] See, e.g., Thomas L. Neff, "Decision Time for the HEU Deal: U.S. Security vs. Private Interests," *Arms Control Today* 31 (June 2001), pp. 12-17. Available as of January 2005, at: http://www.armscontrol.org/act/2001_06/nefjun01.asp. Most recently, USEC succeeded in forcing Russia to accept a new pricing structure that reduces payments to Russia by several tens of millions of dollars a year, compared with the previous agreement. This has generated considerable resentment among some Russian nuclear officials, but for now deliveries of the blended-down material are stabilized and USEC has an economic incentive to carry out the deal as rapidly as possible because the Russian material is now USEC's lowest-cost source of supply.

[93] USEC Fact Sheet, "US-Russian Megatons to Megawatts Program: Recycling Nuclear Warheads into Electricity," USEC Inc., December 31, 2004. Available as of January 2005, at: http://www.usec.com/v2001_02/HTML/megatons_fact.asp.

beginning a large-scale plutonium disposition campaign in reactors. Use of existing European fuel fabrication facilities, at least for fabrication of initial fuel assemblies and perhaps the fuel for the first reactor loads, could significantly accelerate the schedule on which the reactor option could begin.

In the United States, far more reactors than needed have sufficient licensed lifetimes remaining to carry out the plutonium disposition mission, although identifying reactors willing to participate (even given substantial financial incentives) has proved to be a struggle. In Russia, only the eight 950 MWe VVER-1000 light-water reactors (LWRs) and the one BN-600 fast-neutron reactor fall into this category. Depending on the final conclusion about how much plutonium can be safely loaded into these reactors, and depending also on the desired pace of disposition under the MOX option, use of the eleven VVER-1000 reactors in Ukraine (whose fuel has been provided by Russia under long-term agreements) might be considered. Another possibility, proposed by Canada, is to use both U.S. and Russian plutonium in fuel for existing Canadian deuterium-uranium (CANDU) reactors.[94]

Both the United States and Russia have some but not all of the facilities that would be needed to immobilize plutonium with high-level wastes. In the United States, a major effort to vitrify high-level wastes from past reprocessing is just beginning at Savannah River and is planned at Hanford. Plutonium could be added to such waste glasses, but this would require either substantial modifications of existing facilities or the construction of new ones.[95] Russia is already vitrifying high-level wastes at Chelyabinsk.

Under the September 2000 U.S.-Russian Plutonium Management and Disposition Agreement (PMDA),[96] Russia is supposed to

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[94] For a summary of a range of potential approaches to accelerating the rate of plutonium disposition, see Matthew Bunn, Anthony Wier, and John P. Holdren, *Controlling Nuclear Warheads and Materials: A Report Card and Action Plan* (Washington, DC: Nuclear Threat Initiative and the Project on Managing the Atom, Harvard University, March 2003), pp. 156-161.

[95] An alternative method developed by DOE, known as "can-in-canister," also has promise. In this approach, the plutonium would be immobilized in small cans of glass or ceramic without high-level wastes (allowing existing glove-box facilities to be used), and these small cans would be arrayed inside the large canisters into which the high-level waste glass is being poured at the existing vitrification plant.

[96] *Agreement Between the Government of the United States of America and the Government of the Russian Federation Concerning the Management and Disposition of Plutonium Designated as No Longer Required for Defense Purposes and Related Cooperation*. Available as of January 2005, at: http://www.nti.org/db/nisprofs/russia/fulltext/plutdisp/pudispft.pdf.

begin loading 34 tons of excess military plutonium[97] in MOX fuel into civilian reactors around 2008, at an initial rate of 2 tons of Pu per year, increasing thereafter to 4 tons per year. Rosatom (formerly the Ministry of Atomic Energy) has always considered all separated plutonium to be a valuable energy resource irrespective of cost calculations showing that even using "free" military plutonium in fuel is more expensive than making fuel with the same energy value from freshly mined and enriched uranium. Consequently, the PMDA does not commit any Russian plutonium to disposition by immobilization with wastes.

The transparency and monitoring provisions in the PMDA are extensive and are the most informative available "official" wording for purposes of illustrating the complexity and sensitivity of transparency and monitoring procedures for NEM as seen by the two leading nuclear weapon states. Of particular note in these passages are (a) the extensive attention given to how monitoring can be accomplished while protecting information about the composition of the plutonium from the two countries' weapons, which remains classified to varying degrees on both sides and (b) the delicate and ambiguous interplay of bilateral versus multilateral (IAEA) responsibilities and privileges in the verification process, leaving unresolved the question of what the IAEA role actually will be.

The United States agreed under the PMDA to dispose of 34 tons of excess weapon plutonium, as well, and agreed further that at least 25 tons of this would be loaded into civilian reactors in MOX fuel.[98] It had been supposed by many that the United States would choose to use immobilization with wastes for disposition of the maximum amount allowed by agreement—that is, the remaining 9 tons of the declared weapon plutonium surplus, but the Department of Energy announced in February 2002 that the immobilization option in the U.S. disposition program was being set aside as an economy measure, leaving only the MOX option.[99] Aside

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[97] The 34 tons of military plutonium will be blended with 4 tons of Russian reactor-grade plutonium in order to preserve the confidentiality of the isotopic mix in the weapon-grade material.

[98] The United States has declared a larger amount of military plutonium (52.5 tons) surplus to its needs, but 18.5 tons of this total are either reactor grade or highly contaminated and were therefore not credited by the Russians as something they needed to match.

[99] National Nuclear Security Administration, Office of Fissile Materials Disposition, *Report to Congress: Disposition of Surplus Defense Plutonium at Savannah River Site* (Washington, DC: National Nuclear Security Administration, February 15, 2002). Available as of January 2005, at: http://www.nci.org/pdf/doe-pu-2152002.pdf.

from the liabilities of this "all eggs in one basket" approach, this decision poses the problem that 1-2 tons of the 34 consists of material too badly contaminated with other elements and compounds to be purifiable for use in MOX.

Even the slow U.S. and Russian timetables specified in the PMDA are no longer achievable. Discussions of an international financing and management approach for disposition of Russian excess plutonium have dragged on far longer than anticipated in the PDMA, and despite the inclusion of plutonium disposition as a priority item in the $20 billion G8 Global Partnership Against the Spread of Weapons and Materials of Mass Destruction, which raised hopes that sufficient financing would soon be pledged, no conclusion of these talks is yet in sight. Moreover, as a result of a dispute over liability in the event of an accident, the U.S. government was unwilling to extend the agreement that had provided the legal framework for the technical cooperation on plutonium disposition now underway, and that agreement expired in mid-2003. As a result, technical cooperation in preparation for building a MOX plant in Russia has been drastically slowed, and construction of the facility has been delayed by at least a year, and possibly more. Because both the administration and the Congress have linked the start of construction of a U.S. MOX facility to the start of construction of a Russian MOX facility, the U.S. facility has also been delayed by at least a year.[100]

Considerations and Options Looking Ahead

We judge that achieving appropriate transparency and adequate monitoring for final disposition of surplus military NEM pose entangled political and technical challenges that will require further effort to resolve. Notable among these are (a) monitoring the transformation from item-countable objects (pits) to bulk material (e.g., plutonium oxide or mixed oxide powders) in a situation where nearly all of the characteristics of the initial objects and some of the characteristics of the bulk material are classified and so cannot be revealed to the inspectors;[101] (b) coping with processes in which

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[100] See, for example, discussion in Matthew Bunn and Anthony Wier, *Securing the Bomb: An Agenda for Action* (Washington, DC: Nuclear Threat Initiative and the Project on Managing the Atom, Harvard University, May 2004) and references cited therein.

[101] This particular difficulty could be alleviated in the context of bilateral monitoring by the sort of legislatively sanctioned U.S.-Russian agreement on bilateral exchange of classified information that so far has proven elusive, as discussed above. Even achievement of such an agreement, however,

the composition of the material being monitored is continuously changing, in which radiation barriers complicate access, and in which losses to waste products in ways difficult to measure may complicate material accounting; and (c) assaying accurately the plutonium content of spent reactor fuel (in the MOX disposition option), which by the nature of reactor physics and technology will be variable across different fuel elements and even within them. The difficulty of meeting these challenges should not be underrated, but neither should one suppose that they cannot be surmounted.[102] We believe that they are fertile ground for increased U.S.-Russian technical cooperation and joint demonstrations, as well as for trilateral (US-Russia-IAEA) efforts.

Final disposition is a long-term project no matter what its priority and no matter what its pace; it cannot alleviate the need for rapid improvements in MPC&A. As with most long-term projects that are badly needed, however, the difficulty and duration of the disposition project make it all the more important to start early and come up to speed quickly. Large stocks of HEU and separated plutonium, no matter how well accounted for and protected against theft, represent a risk of breakout from nuclear arms limitation agreements by the states that own the material and control the territory on where it is stored, as well as a risk of the material falling into other hands as a result of a major societal disruption.

The longer the wait before the NEM is finally disposed of in ways that make its use in nuclear explosives very unlikely, the greater the chance that currently unforeseen developments could turn it into a major menace. Certainly there are significant transparency and monitoring challenges associated with the processes of final disposition that exceed the challenges of simple guarded storage on a continuing basis. Like the other challenges of disposition, however, we believe that those of transparency and monitoring will likely yield to concerted and cooperative effort if the political will exists to get it done.

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would not permit multilateral involvement in monitoring except through the use of innovative approaches to protect the classified information.

[102] A more extended treatment of the challenges in transparency and monitoring of final disposition, which also summarizes the approaches that have been envisioned for dealing with them, is provided by Annette Schaper, "Monitoring and Verifying the Storage and Disposition of Fissile Materials and the Closure of Nuclear Facilities," in Nicholas Zarimpas, ed., *Transparency in Nuclear Warheads and Materials* (New York: Oxford University Press and Stockholm International Peace Research Institute, 2003), pp. 206-228.

CONCLUSIONS

This chapter has examined the record of and potential for applying monitoring and transparency measures to military and civilian stocks of NEM. In doing so it has addressed, among other issues, the benefits of transparency and monitoring that would be associated with reductions in NEM stocks and flows and in the number of sites where NEM are stored—steps of obvious value in reducing opportunities for NEM theft and diversion—as well as the challenges that transparency and monitoring for the reductions processes themselves would pose. The United States and Russia have acquired substantial experience through their cooperation to improve the security of Russian stocks of NEM, including joint work on technologies and methods for enhanced transparency and monitoring. The work of the IAEA has provided extensive multilateral experience with monitoring and transparency for civilian NEM and some limited experience with military NEM as well.

Accounting, management control, and protection for NEM—the measures collectively referred to as MPC&A, which are pursued by nations for both economic and security reasons and by the international community as part of the nuclear nonproliferation regime—interact with transparency and monitoring in important and multifaceted ways. Transparency and monitoring are of limited value without competent MPC&A. Thus implementing and strengthening MPC&A, in addition to its direct benefits for security, is therefore sometimes the most important step that can be taken toward improved transparency and monitoring. At the same time, improved transparency and monitoring conversely can lead to identification and thus remedy weaknesses in MPC&A. Increases in transparency and monitoring of NEM, if accepted, could also accelerate efforts to strengthen MPC&A through cooperative measures. On the other hand, increased transparency can also complicate the task of MPC&A by providing information useful to those who would steal NEM.

We conclude that:

1. Transparency and monitoring measures for declared stocks of NEM at declared sites, comparable to those for nuclear weapons, could include:
    - comprehensive declarations describing the quantities and locations of all existing inventories of NEM, to-

gether with information on chemical forms and isotopic composition on the material;
- declarations of inventories of NEM surplus to military and civilian needs; and
- provisions for inspections of all declared facilities as well as of any undeclared suspicious activities.

2. A number of additional measures could help to reduce the stocks and flows of NEM, as well as to reduce the number of sites at which NEM are stored. Immediate efforts related to HEU are especially important given its greater utility for terrorists or states seeking simple nuclear weapons. These measures include:
   - accelerated disposition of excess HEU inventories through down blending and eventual use in reactor fuel;
   - replacement of HEU fuels in research reactors with high-density LEU fuels, where feasible, and decommissioning of nuclear reactors using HEU fuels when replacement is not possible;
   - disposition of excess separated plutonium either by conversion to MOX fuel for use in civil reactors or by mixing with fission products and immobilization;
   - a comprehensive cutoff of production of NEM for weapons;
   - a serious international effort to develop nuclear fuel cycles for civil reactors that minimize or eliminate the exposure of NEM; and
   - possible centralization under multinational control of all facilities capable of enriching uranium or reprocessing plutonium.
3. Two efforts that would provide great benefits for international efforts to increase transparency and monitoring for NEM are:
   - continued substantial improvements in national management, protection, control and accounting of all national holdings of NEM so that individual countries, in particular Russia and the United States, are fully aware of the quantity and status of all of their holdings of NEM and have provided effective protection against theft or diversion for all stocks of NEM; and
   - continued strengthening of the safeguards regime administered both bilaterally and by the IAEA, including universal applicability of the Additional Protocol, with

increased manpower and funding to carry out the expanded mandate.

Important efforts to support both these goals are underway, but they should be enhanced and accelerated.

4. Greatly improved management and decreased inventories of NEM, which are priorities on their own account, would be critical if limits on total numbers of warheads were contemplated. The lower such limits became, moreover, the greater would be the need for reduction of NEM stockpiles and high confidence in monitoring the stocks that remained.
5. While the technologies exist to achieve monitoring of NEM quantities with considerable accuracy and confidence under a cooperative framework, a new strengthened international consensus on the value of doing this would be necessary to solve cooperatively the many difficult problems involved.

4

Clandestine Stocks and Production of Nuclear Weapons and Nuclear-Explosive Materials

We concluded in Chapters 2 and 3 that procedures and technology are available to verify with high confidence declarations of stockpiles of nuclear weapons and nuclear-explosive materials (NEM) at declared sites. But undeclared nuclear weapons and NEM could exist as a consequence of retention of undeclared existing nuclear weapons and NEM or could come into existence by the clandestine production of nuclear weapons from existing NEM. In addition, undeclared NEM for weapons might be produced clandestinely or diverted covertly from peaceful nuclear power programs. Current non-nuclear weapon states and possibly terrorist groups might also acquire nuclear weapons or NEM. The potential for clandestine activities in these categories poses the largest challenges to efforts to strengthen transparency and monitoring for nuclear weapons, components, and materials on a comprehensive basis.

This chapter addresses those challenges, asking how and to what degree other states could gain confidence that undeclared nuclear weapons and stocks of NEM do not exist and are not being produced at clandestine facilities. Accordingly, we describe tools and techniques that could be used for two interrelated tasks: (1) to detect undeclared stocks and production activities that might exist and (2) to narrow the uncertainties in declarations that could mask such clandestine activities.

Table 4-1 highlights the key routes by which a state might retain or acquire undeclared nuclear weapons. The most straightforward of these is the retention of existing nuclear weapons at clandestine sites. A state wishing to cheat would simply move some number of weapons to a secret facility and provide a false declaration indicating that these weapons had never been produced or that they had long ago been dismantled. Alternatively, new nuclear weapons could be assembled at a clandestine facility. In this case, the required NEM could be supplied from existing undeclared stocks or could be newly produced at undeclared production facilities. We first discuss tools and techniques for detecting clandestine stocks of nuclear weapons or NEM, if they exist, and then turn to the problem of detecting clandestine production of weapons and NEM. In both cases, we attempt to estimate very roughly the maximum size of an undeclared stockpile or production activity that might go undetected.

TABLE 4-1 Routes to Undeclared Nuclear Weapons

Route to undeclared nuclear weapons	Source of NEM
• Move existing weapons to a clandestine storage or deployment facility	None Required
• Transfer of weapons from another state	
• Assemble new weapons at clandestine facility	• Existing, undeclared stocks at clandestine storage facility • New, undeclared production at clandestine facility
	• Covert diversion from declared stocks or production facility • Transfer from another state

These highlighted routes to undeclared weapons are the principal focus of this chapter. Covert diversion of NEM from declared stocks or production facilities was considered in Chapter 3, where we concluded that the application of safeguards like those used by the International Atomic Energy Agency (IAEA) should be able to detect any significant diversion. We also do not consider here the problem of overt breakout—that is, the open diversion of NEM from declared stocks or production facilities—because this would provide timely warning that the state may be producing undeclared nuclear weapons, which is the purpose of the monitoring system. Nor do we discuss the possibility of theft or transfer of nuclear weapons or NEM from other states. We assume that any significant theft would be detected, and the transfer of weapons or NEM would only shift the problem of detecting a false declaration from one state to another (provided that all such states were subject to equivalent monitoring and safeguards arrangements).

DETECTING UNDECLARED STOCKS OF WEAPONS AND NEM

In order to gain confidence that declarations are complete and that no undeclared stocks of nuclear weapons or NEM exist, states or an inspection agency must have an ability to collect direct or circumstantial evidence of undeclared stocks if they do exist. Direct evidence would be the actual discovery of undeclared weapons or NEM. Circumstantial evidence would include audits of records and physical evidence from which one could infer that it is likely that undeclared nuclear weapons or stocks of NEM exist at some unidentified location.

If a state agreed to declare all of its nuclear weapons and all stocks of NEM, then the discovery of a single weapon or container of NEM not listed in the declaration would *ipso facto* be a violation of the agreement, unless promptly and satisfactorily explained. As noted in previous chapters, an agreement to tag all declared nuclear weapons and containers of NEM would greatly facilitate monitoring, because the discovery of a single weapon or container without a valid tag would be direct evidence of a violation. If tags are not used, the state might claim that the discovered weapons or containers of NEM were not properly listed in the declaration because they had been moved recently and the declaration had not been updated accordingly, or some other excuse that would be difficult to refute incontrovertibly.

National Technical Means

The main problem with discovering undeclared stocks is knowing where to look. Existing storage facilities for nuclear weapons and NEM, such as the bunkers shown in Figure 2-3, are distinctive and easily detected and identified using National Technical Means (NTM), in particular high-resolution satellite photography.[1] Any such facilities that were omitted from the declaration would be high priorities for challenge on-site inspections. But a state wishing

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[1] NTM also include other satellite-borne sensors, as well as ground- and sea-based receivers that collect a broad range of signals intelligence. Such information collection is acceptable under international law by sensors located outside the borders or above the sensible atmosphere of the state being inspected. States may also enter into agreements that allow ground- or air-based sensors to be located on or flown above the territory of a state subject to inspection. This is a feature of the Open Skies Treaty and the Comprehensive Nuclear Test Ban Treaty.

to cheat could be expected to select a building that would give few indications of its contents, such as a warehouse in an industrial complex, with few outward signs of high security or other activities usually associated with the storage of nuclear weapons or NEM. Nuclear weapons and containers of NEM are small—even a house-size building could hold hundreds of weapons (or enough NEM for hundreds of weapons). The number of personnel and traffic to the clandestine facility could be kept to a minimum and given a plausible cover story. NEM components or containers of bulk material need little or no maintenance. Nuclear weapons require periodic inspections and the replacement of limited-life components, such as batteries or tritium, but this could be accomplished without attracting attention. If necessary, weapons and materials could be moved between clandestine facilities using commercial vans or trucks, with no security escort.

Nuclear weapons and NEM give few clues about their existence within a facility. NEM emits neutrons and gamma rays, but these radiations are easily shielded and are detectable only at relatively short range (on the order of 100 meters or less) even without shielding. Barring a severe accident, such as the detonation of the high explosive in a weapon, the likelihood that a clandestine storage facility would be detected using NTM probably would be low. One might intercept communications indicating suspicious activities that may be related to nuclear weapons or NEM, but such opportunities would be limited given the relatively low level of activity and small numbers of people required to maintain clandestine stocks.

Human Sources

The surest way to locate a clandestine storage facility for undeclared nuclear weapons or NEM is through human intelligence—for example, the leak of information by someone who has knowledge of the hidden stocks. Governments have varied in their ability to maintain secrecy. The case of Mordechai Vanunu, a nuclear technician who claimed to have personal knowledge of Israel's undeclared nuclear weapon activities, was widely publicized. Even oppressive and secretive governments such as Iraq and North Korea have experienced high-level defectors. While in the United States the secrecy of some major programs was apparently well kept, the general outlines of the Manhattan Project, as well as many sensitive technical details, were known to the Soviet Union through individuals associated with the U.S. nuclear weapons program. Over the years, there have been many serious leaks from highly sensitive U.S. and Soviet programs, motivated by ideology or greed. The extent to which a covert program may have been compromised by individuals within the program or by knowledgeable outsiders can never be known with certainty by a state undertaking the secret program.

One may be able to increase the probability that individuals would report activities that contravene international agreements to international authorities. If the individuals most likely to have knowledge of undeclared activities can be identified, inspectors can request confidential interviews with these people. Such interviews have been used by the IAEA to resolve uncertainties and investigate possible violations of safeguards agreements. Individuals also could be encouraged to come forward on their own, by requiring that states pass domestic laws making it illegal for individuals to participate in activities that contravene an international agreement, requiring that individuals report violations to a designated international commission, and guaranteeing immunity for the "whistle blowers." This concept, which is sometimes called "societal verification,"[2] received a favorable review by former Under Secretary General for Disarmament Affairs of the United Nations, Jayantha Dhanapala.[3] Societal verification might serve as an additional deterrent to governments contemplating whether to establish a clandestine stockpile of weapons or NEM. A government wishing to cheat would attempt to screen participants to eliminate potential whistle-blowers, but it could never be absolutely and forever certain of their loyalty to the regime.

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[2] Joseph Rotblat, "Societal Verification," in Joseph Rotblat, Jack Steinberger, and Bhalchandra Udgaonkar, eds., *A Nuclear-Weapon-Free World: Desirable? Feasible?* (Boulder, CO: Westview Press, 1993), pp. 103-118. Joseph Rotblat, "Citizen Verification," Bulletin of the Atomic Scientists 48 (May 1992), pp. 18-20 and Richard L. Garwin, Appendix H "Theater Missile Defense, National ABM Systems, and the Future of Deterrence," in Naval Studies Board, National Research Council *Post-Cold War Conflict Deterrence* (Washington, DC: National Academies Press, 1997), pp. 182-200. Available as of January 2005, at: http://bob.nap.edu/html/pcw/Dt-h.htm.

[3] Jayantha Dhanapala, "Civil Society and the Verification of Disarmament," workshop on "Societal Verification" at the Hague Appeal for Peace conference, May 13, 1999. Available as of January 2005, at: http://www.un.org/Depts/dda/speach/13May1999.htm.

Audits of Records

The probability that clandestine stocks would be discovered and directly observed cannot be assumed to be high. Fortunately, there are ways that an inspection agency or other states might gather circumstantial evidence of the existence of undeclared nuclear weapons and stocks of NEM. One can examine the original records for the assembly and disassembly of nuclear weapons and the production and use of NEM, for example, to check their authenticity, internal consistency, and consistency with the declaration and with intelligence information. An examination of operating records is similar to a financial audit, in which a company's records are examined to verify the legitimacy and accuracy of transactions, and that balances accurately reflect receipts and disbursements. It is reasonable to assume that the assembly and disassembly of every nuclear weapon was documented in the operating records of each assembly facility. The declared inventory of each weapon type should equal the total recorded number assembled minus the number disassembled. In order to hide existing nuclear weapons, the records would have to be falsified to indicate either that the hidden weapons had never been assembled, or that they had been disassembled or explosively tested at an earlier date.

The authenticity of original paper records, if they still exist, could be verified using standard forensic techniques, which should be able to detect any recent alterations. The records also could be examined for any unusual patterns—for example, periods of low assembly or high disassembly rates or of highly uniform assembly or disassembly rates—that might indicate attempts to falsify the records to hide the existence of undeclared weapons. Finally, archived national intelligence information could be checked for consistency with the operating records provided. Imagery taken by photoreconnaissance satellites might show activity at variance with the records—for example, movements of large numbers of weapons out of or into the plant during periods when the operating records showed little or no activity.

Operating records for NEM production facilities also could provide evidence about the existence of undeclared weapons, or undeclared stocks of NEM that could be used to assemble them. The declared inventories of highly enriched uranium (HEU) and plutonium should be consistent with original records for the production and use of these materials, and the records should be internally consistent. In the case of a uranium enrichment plant, for example, the recorded receipts of uranium entering the plant as feed should be consistent with recorded shipments of HEU and discharges of depleted uranium. Over a given period, the mass of uranium and U-235 in the feed should equal the masses of uranium and U-235 in the HEU and the depleted uranium combined, with some margin of error due to measurement uncertainties. In addition, records of the separative work performed could be compared with the capacity of the plant, which can be verified through design documents and on-site inspections.

The material balance will depend on the design and operation of the plant, but for illustration, consider a plant that produces HEU and depleted uranium with U-235 concentrations of 90 percent and 0.35 percent, respectively. For every 1,000 kilograms of natural uranium entering the plant, 4 kilograms of HEU and 996 kilograms of depleted uranium are produced. The feed contains 7.1 kilograms of U-235, of which 3.6 kilograms goes into the HEU and 3.5 kilograms goes into the depleted uranium.

Similar methods could be applied to verifying declarations of plutonium production. This would involve examining records of the fabrication of uranium fuel and target rods for production reactors; the design of the fuel and the reactors, typical fuel loadings in the core, and dates of fuel loading and discharge; monthly production of thermal energy; shipments of spent fuel; the design of the reprocessing plants; monthly production of plutonium product; and the volume, isotopic composition, and disposition of the various waste streams.

As with weapons, archived intelligence information might be checked for consistency with the records; for example, imagery of a plutonium production reactor or a gaseous diffusion enrichment plant could indicate whether the plant is operating and, at least roughly, the level of production. Production records for NEM could also be checked for consistency with records for weapon assembly. In the case of gaseous diffusion plants, records of enrichment work performed might also be checked against records of electrical consumption.

This method of verifying production declarations would depend on the accuracy, completeness, and authenticity of the records that were provided. As noted above, the authenticity of paper records can be verified, but the original records might have been lost or destroyed, and electronic records may be impossible to authenticate. Moreover, even authentic records may be unintentionally inaccurate or incomplete. Record keeping was not exemplary in the early days of most nuclear weapon programs, when the emphasis was on producing material and weapons as quickly as possible. Although record keeping presumably was good for weapons, plutonium, and HEU, it is less likely that accurate records were kept for less valuable materials, such as natural or depleted uranium or reprocessing wastes, which are important for accounting purposes.

Physical Evidence

A variety of methods exist for gathering physical evidence that could be used to confirm NEM production records and resolve uncertainties or apparent discrepancies in them. These methods are sometimes referred to as "nuclear archaeology." In the case of graphite-moderated plutonium production reactors, for example, isotope ratios of impurities in the graphite can provide an accurate estimate of the total integrated neutron flux that was available to produce plutonium during the life of a reactor.[4] Isotopes of various common impurities capture neutrons and produce heavier isotopes of the same element. The ratios of the resulting stable isotopes can be accurately measured by mass spectrometry. By comparing these isotopic ratios with those occurring naturally, the integrated neutron flux at the point of capture can be determined. This method is particularly attractive in that it does not depend on the original concentration of the impurity in the tested items, but only on the ratios of remaining isotopes. A model of the neutron flux with the reactor, however, is essential to relate such measurements accurately to the plutonium produced during the life of the reactor.

Titanium has been identified as a particularly attractive impurity for this purpose. A number of other elements that exist as impurities in graphite would allow independent checks. Measurements of titanium isotope ratios in graphite core samples reportedly can give error margins as low as 2 percent on total plutonium production, assuming that the relevant neutron capture cross sections will be measured more accurately.[5] For a relatively small cost, the plutonium production from all of the 13 former graphite-moderated Soviet production reactors, which produced essentially all the Russian Federation's plutonium, could be esti-

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[4] Thomas W. Wood, Bruce D. Reid, John L. Smoot, and James L. Fuller, "Establishing Confident Accounting for Russian Weapons Plutonium," *Nonproliferation Review* 9 (Summer 2002).

[5] Talbert, R. J., et al. "Accuracy of Plutonium Production Estimates from Isotope Ratios in Graphite Reactors," PNL-TEC 0693 (Richland, WA: Pacific Northwest Laboratory, February 1995).

mated in this way. The Russian Federation has made plans to entomb the closed-down production reactors under radiation barriers, after which it will be much more difficult and expensive to carry out nuclear archaeology. As of early 2005, however, these plans had not moved forward, so the opportunity remains. Although there have been discussions of a joint U.S.-Russian experiment on one of the reactors and some proposals have been developed, it had not been funded as of early 2005.

The United States has used both graphite- and heavy-water-moderated reactors to produce plutonium. The nine graphite-moderated reactors at Hanford reportedly produced 76.4 tons of plutonium; with an accuracy of 2 percent this implies an uncertainty of about 1.5 tons. The five heavy-water-moderated reactors at Savannah River produced 36.1 tons of plutonium. A comparable technique has not yet been developed for heavy-water reactors, and the fractional uncertainty would most likely be larger.

In principle, the cumulative production of HEU could be calculated by determining the total amount of U-235 stripped from the stocks of depleted uranium produced by the enrichment facility. In practice, however, a comprehensive inventory of depleted uranium stocks of U.S. and Russian would be very difficult and costly, and the resulting estimate of HEU production probably would not be sufficiently accurate to be useful. As an indication of the magnitude of the problem, the U.S. Department of Energy stores about 500,000 tons of depleted uranium, mostly in the form of uranium hexafluoride in some 60,000 steel cylinders at three U.S. enrichment plants. This depleted uranium resulted from the production of HEU at various enrichment levels for nuclear weapons and fuel for naval, research, and test reactors, as well as LEU at various enrichment levels for civilian reactor fuel. Moreover, the isotopic composition of the feed varied significantly, including partially depleted and slightly enriched uranium recovered from irradiated reactor fuels in addition to natural uranium. Finally, a small fraction of the depleted uranium discharged from U.S. enrichment plants has been used for various defense and commercial purposes, such as tank armor, armor-piecing munitions, ballast, and radiation shielding. Russian stockpiles of depleted uranium are likely comparable in size and in the complexity of their production history.

Information from depleted uranium might be useful in cross-checking production records, however. It would be possible, for example, to date accurately the contents of the individual cylinders of uranium hexafluoride using the decay products of the uranium isotopes, and to determine by the ratios of U-234 to U-235 whether these particular tails resulted from the production of HEU or low enriched uranium (LEU).[6] If the depleted uranium cylinders are numbered and if these numbers are documented in the operating records, measurements on a random sample of cylinders could be used to confirm the accuracy of the records.

South Africa: Verifying the Completeness of Declarations

South Africa presents an important case study in verifying the completeness of declarations. Having built six gun-type nuclear weapons during the 1980s, South Africa decided to dismantle its weapons and join the Nuclear Non-Proliferation Treaty (NPT) as a non-nuclear weapon state. Beginning in July 1990, South Africa dismantled all its weapons, decommissioned its production and assembly facilities, and recast the HEU weapon components into standard shapes for storage and international inspection.

In March 1993 President de Klerk announced that South Africa had built and dismantled six nuclear weapons. The IAEA was given a full history of the nuclear weapon program, along with a list of the people involved in it. The agency was granted permission to conduct inspections at any relevant location and to interview former managers and workers about the program. A special team of inspectors easily confirmed that the declared amount of HEU had been placed in storage and that weapon-related activities had ceased at various declared facilities. Verifying that the declaration was complete—that South Africa had dismantled all of its weapons and placed all of its HEU under safeguards—was considerably more difficult, however.

The IAEA requested the historical production records from South Africa's uranium enrichment plant. Inspectors used these records, along with other technical and design documents, to recalculate the plant's daily production over the entire period and to produce an overall material and isotopic balance. On the basis of these studies, together with examination of the facilities and interviews of facility personnel, the IAEA concluded that the amount of HEU that could have been produced was consistent with the amount in South Africa's initial declaration within an acceptable margin of uncertainty—less than 25 kilograms, or roughly 5 percent of the declared inventory of HEU. The IAEA therefore con-

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[6] Steve Fetter, "Nuclear Archaeology: Verifying Declarations of Fissile Material Production," *Science and Global Security* 3 (1993), pp. 237-259.

cluded that there was no evidence that South Africa's declaration was incomplete; that is, there was no evidence of the existence of undeclared weapons or significant amounts of undeclared HEU.[7]

A comprehensive assay of the 370 tons of depleted uranium tails, which are stored on-site in some 600 cylinders, would have reduced somewhat the uncertainty in the material balance, but the IAEA decided that the increased confidence provided by such measurements would not justify the considerable expense. Measurements of certain samples were performed, however, which confirmed IAEA calculations (based on the original production records) indicating that substantially more U-235 was contained in the depleted uranium than had been recorded in the official accounting records. These measurements were an important piece of evidence that allowed the IAEA to conclude that there was no evidence of any missing HEU.

The IAEA experience in South Africa illustrates that high confidence in the completeness of declarations can be achieved with a high level of cooperation and transparency. But it also demonstrates that uncertainties will exist and may be difficult to resolve. Verifying South Africa's HEU declaration was complicated by the fact that uranium had also been enriched for nonweapons purposes, and poor records were kept of wastes and materials not valuable for the weapons program. According to then-Director General Hans Blix, "There is inherent difficulty in verifying the completeness of an original inventory in a country in which a substantial nuclear program has been going on for a long time."[8] The irony is that South Africa's nuclear program, which produced a total of six weapons, may prove to be the smallest and shortest lived of all programs that produced a nuclear weapon. We believe that the difficulties experienced by the IAEA in verifying South Africa's declaration are likely to be much more difficult for the *de jure* nuclear weapon states, making it much more difficult to conclude that their declarations are complete.

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[7] Adolf von Baeckmann, Gary Dillon, and Demetrius Perricos, "Nuclear Verification in South Africa," *IAEA Bulletin*, 37 (March 1995). Available as of January 2005, at: http://f40.iaea.org/worldatom/Periodicals/Bulletin/Bull371/baeckmann.html.

[8] Hans Blix, Statement to the 36th Session of the General Conference of the IAEA, Sept. 21, 1992.

Uncertainties in Weapon and NEM Stockpiles

As noted above, if a country retained undeclared stocks of weapons or NEM, there would be some chance that these would be detected and directly observed as a result of intelligence collection or information provided by individuals with knowledge of the stocks. If original operating records had been falsified to hide the existence of undeclared stocks, detection of such falsifications would be seen as convincing evidence of an attempt to cheat. Otherwise, the only evidence of hidden stockpiles would be an imbalance of NEM calculated or inferred from an examination of the operating records and physical inventories. Here we consider the likelihood that the existence of undeclared stocks of NEM could be inferred based solely on these statistical methods. The actual likelihood of detecting undeclared stocks of a given size would be greater than given here, however, because of the other possible sources of information listed above.

Even the most exhaustive examination of operating records and the most thorough physical inventory is likely to result in NEM estimates with a margin of error of at least a few percent. As discussed in Chapter 3, the official U.S. estimate of the total amount of plutonium produced or otherwise acquired by the United States is 2.8 tons greater than the measured amount of plutonium in current stockpiles plus the estimated amounts removed from the inventory in nuclear tests, wastes, reactor burnup, and other transfers. This "inventory difference," which amounts to 2.5 percent of total plutonium production, is the combined result of errors in measurement and record keeping, overestimates of the amount produced in reactors, and underestimates of the amount of plutonium in wastes. Inventory differences for HEU production are likely to be even larger.

All things considered, the accounting uncertainties in plutonium and HEU stocks are likely to be no smaller than 2 and 4 percent, respectively.[9] To put this in perspective, Table 4-2 expresses the estimated uncertainties in total plutonium and HEU inventories of the *de jure* and *de facto* nuclear weapon states in terms of an approximate number of "Significant Quantities" as defined by the

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[9] In this discussion the "accounting uncertainty" is defined as two standard errors, in which case there is a 5 percent chance that the difference between the actual stock and the estimated stock is greater than the accounting uncertainty. The estimated stock plus or minus the accounting uncertainty is the 95 percent confidence interval for the actual stock, meaning that there is a 95 percent chance that the actual stock is within this range.

IAEA.[10] The amount of material that could be diverted, however, with low probability of arousing suspicion by statistical means alone is much smaller—roughly five times smaller than these accounting uncertainties (see Box 4-1). Based on this, as well as the fact that nuclear weapon states could produce more than one nuclear weapon per significant quantity (see below), we judge that Russia and the United States probably could confidently conceal from statistical detection undeclared NEM stocks equivalent to several hundred nuclear weapons; the United Kingdom, France, and China could conceal undeclared stockpiles equivalent to one or two dozen weapons; and Pakistan, Israel, and India may be able to conceal enough NEM for at most one or two weapons.

TABLE 4-2 Uncertainties in Plutonium and HEU Inventories (Number of Significant Quantities)

	2% of Estimated Pu Inventory	**4% of Estimated HEU Inventory**	**Total SQ**
Russia	400	1700	2000
United States	250	1100	1400
France	10	50	60
United Kingdom	20	40	50
China	10	30	40
Pakistan		2	2
Israel	1		1
India	1		1
North Korea	<1		<1

One Significant Quantity is defined by the IAEA as 8 kilograms of plutonium or 25 kilograms of HEU. The sum of the Pu and the HEU may not add up to the total due to rounding.

Adapted from: David Albright, *Global Fissile Material Inventories*, June 2004. Available as of January 2005, at: http://www.isis-online.org/global_stocks/tableofcontents.html.

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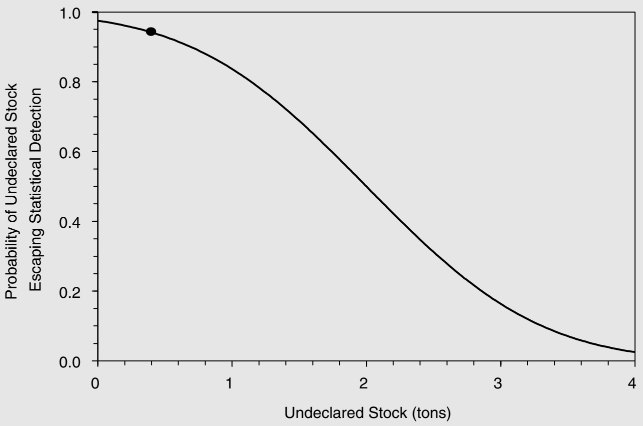
[10] As noted in Chapter 3, a Significant Quantity is the amount of NEM the IAEA considers sufficient to manufacture a first nuclear weapon; it is defined as 8 kilograms of plutonium or 25 kilograms of HEU.

BOX 4-1

Accounting Uncertainty and the Probability of Statistical Detection

A common misperception is that a party could divert material up to the accounting uncertainty without fear of detection. To see that this is incorrect, assume that the inspected party's total stock of NEM is 100 tons and that the uncertainty in the inspecting party's estimate of this stock is ±2 tons. The figure below gives the probability that an undeclared stock of a given size would escape statistical detection (i.e., that the declared stock would fall below the 95% confidence interval estimated by the inspecting party). For example, if the inspected party failed to declare 0.4 tons (one-fifth of the accounting uncertainty), the probability that this undeclared stock would escape detection is 94%. Note that the probability of escaping detection drops sharply as the size of the undeclared stock increases beyond this point. Thus, the inspected party could not be highly confident that undeclared stocks much larger than one-fifth of the accounting uncertainty would escape statistical detection by the inspecting party.



The actual situation would be more complex for a number of reasons. First, the above example assumes that the inspecting party's estimate of the actual stock is unbiased, but bias of some type is inevitable and is difficult to evaluate quantitatively. Second, the uncertainty in the inspecting party's estimate (and any bias that may exist) would depend on the inspection process itself (e.g., examination of records, physical measurements, etc.) and would not be known in advance, complicating assessments of the size of the undeclared stock that would confidently escape detection. Third, the inspecting party's interpretation of the results would depend on its prior estimate of the probability that the inspected party is cheating (see Footnote 18 in chapter 2). If the inspecting party's prior probability of cheating is high (because of other suspicious behavior or evidence), then declarations that lie below the estimated confidence interval would greatly strengthen the case that the inspected party was cheating.

These uncertainties are associated with the stock of NEM. This was the only major uncertainty in South Africa's declaration, because in this case the entire declared stock of HEU was available for inspection. But if a state also maintains substantial declared stocks of nuclear weapons or weapon components, the inspecting party would also have to consider uncertainties in its knowledge about the amount of NEM in these weapons and components. Suppose, for example, that a state declared a total stockpile of 500 kilograms of plutonium, contained entirely in 100 weapons. Even if the inspecting party was absolutely confident that the state had produced no more than 500 kilograms of plutonium, it could not be sure that there were no undeclared weapons unless it could also confirm the amount of plutonium in the declared weapons. If the declared weapons each contained 4 kilograms of plutonium, then there might be a hidden stockpile of 25 undeclared weapons.[11]

For this reason, we believe it would be very helpful if declarations specified the amount of NEM in each type of weapon. These amounts, which the nuclear weapon states currently consider highly classified information, might vary by a factor of two or more between different weapon designs. Although existing techniques and procedures could be adapted to permit verification of declared amounts of NEM in randomly selected weapons without revealing other sensitive weapon design information, this degree of transparency probably is not acceptable to the nuclear weapon

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[11] The 4 kilogram estimate is the planning figure used in Committee on International Security and Arms Control, *Management and Disposition of Excess Weapons Plutonium* (Washington, DC: National Academy Press, 1994), p. 19.

states under current conditions. As explained in Chapter 2, such sensitive information could initially be exchanged in encrypted or digest form, to be decoded only by mutual agreement to resolve questions in connection with verifying declarations in the event that arsenals were reduced to low levels where high accuracy of accounting would take on added significance.

If substantial numbers of nuclear weapons were disassembled and their NEM components converted into bulk materials while declarations and associated transparency measures are in place, the inspecting party would over time develop increasing confidence in the declared amounts of NEM in the remaining weapons and components. For instance, if in the above example the state dismantled 50 weapons of a given type and in the process turned over 250 kilograms of plutonium, then one could be reasonably confident that the remaining 250 kilograms was contained in the 50 weapons remaining in the declared stockpile.

DETECTING UNDECLARED PRODUCTION OF WEAPONS AND NEM

The other main route to the acquisition of undeclared nuclear weapons is to produce new weapons in undeclared production and assembly facilities. The key elements of such a program are shown in Figure 4-1. We assume that most or all of these activities would occur in clandestine facilities, because the monitoring and inspection procedures discussed in Chapters 2 and 3 would be designed to prevent the undetected use of civil or other declared facilities for significant undeclared activities.

A complete program to produce nuclear weapons is a substantial undertaking, even for a highly experienced and technologically advanced state. Many of the activities shown in Figure 4-1 would be difficult to conceal in a cooperative environment in which a country is required to declare all of its nuclear facilities and is subject to routine inspection of these facilities and challenge inspections of any suspicious activities. In general, the construction and operation of facilities for the production of NEM are the most easily detected activities. Detection would be more difficult if the weapon program were embedded in a large civil nuclear program, and more difficult still if NEM were obtained from existing clandestine stocks or from an external source, obviating the need for telltale production facilities.

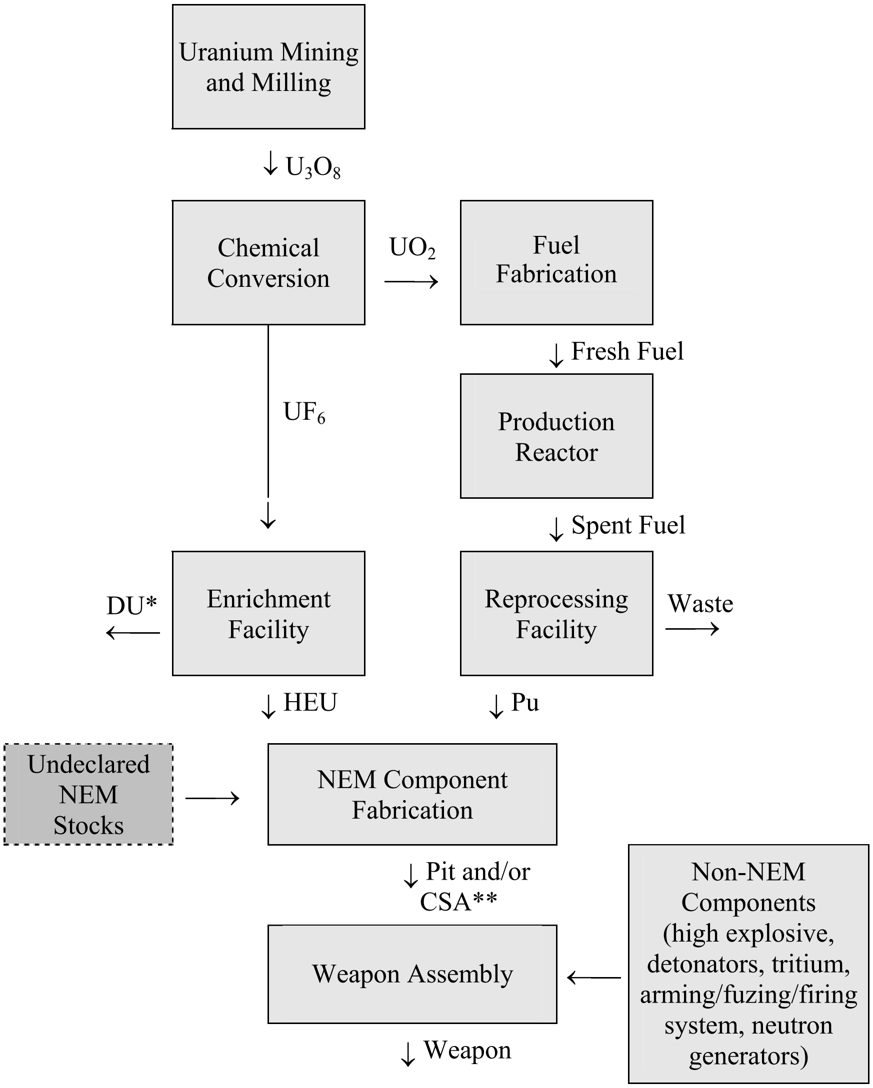

FIGURE 4-1 Key elements of a program to produce nuclear weapons.
*DU = Depleted Uranium;
**CSA = Canned Subassembly

There are a number of powerful tools available to the United States and the international community, including national technical means, human intelligence, and environmental monitoring, that are able to gather evidence of any clandestine nuclear activities that may exist. These tools would be most effective in conjunction with the right to obtain confirmation by on-site inspections of suspicious activities that have been identified.

National Technical Means

The principal means of uncovering evidence of clandestine production of NEM or nuclear weapons would be provided by NTM; for example, mining and milling operations can easily be identified using photoreconnaissance satellites. A clandestine program to produce 10 Significant Quantities of HEU or plutonium per year would require 40 to 80 tons of natural uranium per year,[12] as well as chemical facilities to convert it into forms appropriate for enrichment or fuel fabrication. Extending declarations to include the location of uranium mines would make undeclared uranium mining and milling activities more vulnerable to detection. Inspectors could visit a random sample of mines in districts where it is believed that uranium ores are present in order to confirm the absence of undeclared uranium mining and milling operations. Extending safeguards to include yellowcake production would make it difficult to divert uranium from safeguarded mills to clandestine chemical conversion facilities. NTM (e.g., signals intelligence) could also detect attempts to secretly import uranium from other countries.

Existing plutonium and HEU production facilities are quite distinctive and are easily detected and identified using photoreconnaissance satellites. A state wishing to cheat would, of course, attempt to hide or disguise the construction and operation of undeclared facilities, but this is practically impossible for plutonium production. Although a clandestine reprocessing facility might conceivably be hidden underground, it would require an undeclared source of spent fuel. A plutonium production reactor is

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[12] Producing 1 kilogram of HEU (90 percent U-235) requires 180 to 290 kilograms of natural uranium feed, depending on the tails assay (0.2 to 0.4 percent U-235), or 4.4 to 7.2 tons of uranium per significant quantity of HEU (25 kilograms). Producing 1 kilogram of plutonium (6 percent Pu-240) requires about 1,000 kilograms of natural uranium, for a reactor fueled with natural uranium and moderated with graphite or heavy water, or 8 tons of uranium per significant quantity of plutonium (8 kilograms).

necessarily a large facility with special features and equipment. Even if the reactor itself could be hidden (which seems unlikely), the unavoidable discharge of waste heat into the environment would be detectable by infrared sensors on satellites. A reactor capable of producing 10 Significant Quantities of plutonium per year would have a thermal power of about 250 megawatts—equal to the heat output of a small city.

The gaseous diffusion enrichment plants built by several of the nuclear weapon states are easy to detect by virtue of their enormous size, electrical power requirements, and heat output. A small gas centrifuge enrichment plant, on the other hand, would be much easier to conceal or disguise. A plant capable of producing 10 Significant Quantities of HEU per year would require on the order of 10,000 centrifuges, with a floor area of roughly 10,000 square meters and a power consumption of about 300 kilowatts, which is comparable to many large commercial and industrial buildings.[13]

The final steps are the fabrication of weapon components and assembly of the weapon. Although in the past these activities typically have been conducted in distinctive facilities, this need not be the case, particularly if a state is willing to accept lower levels of safety and security. Among the most distinguishing features of the U.S. Pantex weapon assembly facility, for example, are the assembly cells, which are designed to withstand the accidental detonation of high explosives and prevent dispersal of plutonium. If a state were willing to accept higher risks of theft and dispersal of NEM and higher risks to worker health and safety, component fabrication and weapon assembly could take place in almost any large building.

The physical appearance of facilities can give important clues about their function and possible relationship to a clandestine weapon program, but this is only one piece of the intelligence puzzle. The flow of special materials, equipment, and components—particularly items imported from other countries—and particularly the intercept of communications between certain individuals also can provide valuable information about the existence and location of undeclared activities, which can then be used to focus attention on particular facilities.

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[13] This example assumes 200 separative work units (SWU) per kilogram of HEU and centrifuges with a capacity of 5 SWU per year and a power consumption of 50 kilowatt-hours per SWU.

Human Sources

NTM is supplemented by information from various human sources, including reports in the open literature, travelers, defectors, and individuals within the program itself. As noted above, the likelihood that individuals with knowledge of illegal activities would report these violations to international authorities can be enhanced in a number of ways. Human sources are likely to be much more valuable in detecting the undeclared production of nuclear weapons or NEM, compared with the detection of undeclared stocks, simply because of the far greater number of individuals that would be involved in building and operating production facilities. The secret South African weapons program, for example, which produced six nuclear bombs, reportedly employed a total of 1,000 people (but no more than 300 at any one time);[14] thousands more were likely employed in nonsecret uranium mining and milling, chemical conversion, and uranium enrichment operations. Although a completely clandestine program conducted by a state experienced in nuclear weapons technology could be smaller, at least several hundred people would be required. A state wishing to cheat could compartmentalize knowledge and attempt to deceive workers about the true nature of the program, but this would be difficult in an environment where it is widely known that all nuclear activities must be declared and are subject to inspection by international authorities. A leak or defection by only one of the hundreds of people involved could be enough to expose the program and trigger requests for on-site inspections of undeclared production facilities.

Environmental Sampling and Monitoring

The processing and enrichment of uranium, the operation of a nuclear reactor, and the reprocessing of spent reactor fuel inevitably release materials into the environment that are uniquely characteristic of these activities. These effluents can be in the form of gases, liquids, and fine particles released during normal facility operations or during accidents. Traces of these effluents can be detected in environmental samples collected during on-site inspections at facilities or monitoring stations as a component of an agreement or NTM.

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[14] Mitchell Reiss, *Bridled Ambition: Why Countries Constrain Their Nuclear Capabilities* (Washington, DC: Woodrow Wilson Center Press, 1995), p. 14.

Environmental sampling is most powerful in detecting undeclared activities at declared or suspect facilities. Small particles may be deposited throughout and around a facility, both within and outside of areas where NEM and related materials are handled. These particles can be collected with "swipe samples" during on-site inspections (e.g., by wiping a piece of filter paper on a wall or the inside of a process tank). Recent examples include the collection by IAEA inspectors of plutonium particles in the North Korean reprocessing facility, and HEU particles in the Iranian centrifuge enrichment facility. The particles are analyzed using mass spectrometry to determine their elemental and isotopic composition. In this way, inspections can indicate whether uranium has been enriched or whether any reprocessing has occurred at the facility. Isotope ratios can also be used to establish whether uranium has been enriched above a given level, and the burnup of the fuel that was reprocessed and the date that reprocessing or other purification processes occurred. It is highly likely that any significant, undeclared enrichment or reprocessing operations could be detected by environmental sampling at the suspect facility.

Effluents can also be carried many kilometers downwind or downstream from the facility, where they may be detected by sampling air, soil, vegetation, water, and sediments. The Comprehensive Nuclear Test Ban Treaty (CTBT) provides for a network of 80 air-sampling stations to detect radioisotopes released from clandestine nuclear tests. Similar "wide-area" environmental sampling networks have sometimes been proposed to detect clandestine production of NEM. The ability of wide-area environmental sampling to detect such activities depends primarily on the amount of effluent released, which in turn depends on plant design as well as the diligence and experience of plant operators. Also important are meteorological conditions and the existence of background signatures produced by nearby civil nuclear facilities, fallout from atmospheric nuclear testing in the 1950s and early 1960s, and from the 1986 Chernobyl reactor accident. The sensitivity and specificity of environmental sampling are generally dependent on variables that neither the monitor nor the proliferator can reliably predict.

Many long-lived radioisotopes are produced in the fuel elements of a nuclear reactor during its operation. Some of these radioisotopes are volatile and can be released into the environment if fuel elements rupture inside a reactor, or when the spent fuel is dissolved in a reprocessing plant. The long-lived radioisotope krypton-85 is an especially valuable signature of reprocessing activity, because it is very difficult to prevent the release of noble gases. Only extreme measures, such as cryogenically trapping all effluents, can trap noble gases. The technology to detect radioactive xenon from nuclear tests is highly developed,[15] and similar techniques could be applied to the detection of radioactive krypton. Other radioisotopes, in particular cesium-137, strontium-90, plutonium-239, and plutonium-240, could be released in amounts detectable at long ranges as a result of accidents at reprocessing facilities.

Releases from uranium conversion and enrichment facilities generally are less detectable than releases from reactors and reprocessing facilities, depending on the technology used and the likelihood of accidents. Because the uranium compounds used in enrichment (e.g., uranium hexafluoride) are quickly oxidized to naturally occurring uranium compounds, only particles containing enriched (or depleted) uranium are usually detectable and would be uniquely indicative of the existence of a uranium enrichment facility. Centrifuge enrichment facilities can have extremely low routine release rates, although a large pipe break or the failure of a number of centrifuges might release significant amounts of enriched uranium into the environment. Gaseous diffusion and electromagnetic separation facilities have much larger routine release rates, but it is highly unlikely that a state wishing to clandestinely produce HEU would use these older, much less efficient, and far more detectable technologies, unless they were unable to develop or otherwise acquire centrifuge technology.

A 1999 report by an IAEA group representing 26 member states provides useful information on the sensitivity of environmental monitoring required to detect clandestine facilities producing Significant Quantities of NEM (i.e., 8 kilograms of plutonium or 25 kilograms of weapons-grade uranium annually).[16] The report

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[15] T.W. Bowyer, et al, "Field Testing of Collection and Measurement of Radioxenon for the Comprehensive Test Ban Treaty," *Journal of Radioanalytical and Nuclear Chemistry* 240 (1999), pp. 109-122. Technologies to detect trace amounts of radioactive xenon from nuclear tests have been developed by the Pacific Northwest National Laboratory. This same approach can be used to greatly improve detection of the radioactive products of reprocessing. Air samples are compressed and cooled to trap trace amounts of xenon and krypton. The automated radio xenon sample analyzer (ARSA) uses narrow energy windows in detecting in coincidence the conversion electrons and gamma rays to greatly reduce the background. ARSA detects the short-lived xenon activities to a threshold level of 0.00006 decays per second per cubic meter (0.06 mBq/m^3).

[16] IAEA, "Use of Wide Area Environmental Sampling in Detection of Undeclared Nuclear Activities," Member States Support Programmes to the IAEA, STR-32, April 27, 1999.

relied primarily on data on historical releases from existing facilities as a reference. Releases from a clandestine facility might be considerably higher or lower, depending on the operator's level of technical expertise and the care taken to minimize releases. In general, a technically advanced state operating with a substantial budget and without undue pressure to meet tight deadlines could be expected to build and operate a clandestine facility with very low emissions, while an inexperienced state with limited resources or an experienced state engaged in a crash program might be much less successful in controlling releases. The study concluded that air sampling was the most promising technique. In general, soil and vegetation sampling are less sensitive methods of detecting atmospheric releases, and water and sediment sampling are unlikely to be effective unless effluents are discharged directly into waterways.

The IAEA study used the known emissions from the Sellafield plant in the United Kingdom to estimate the emissions of a hypothetical smaller, clandestine reprocessing plant. The IAEA study estimated that the krypton-85 released from a small reprocessing facility could be detected by a continuous gas sampler at distances of over 100 kilometers downwind under stable atmospheric conditions, with high detection probability and low false alarm rate. The study concluded that a network of 26 sampling stations would have a high probability of detecting the operation of a clandestine reprocessing facility within the portion of a million square kilometer area of the Middle East most capable of supporting a clandestine facility.[17] In addition, particulate sampling may be useful for detecting accidents at reprocessing plants. Because of the relatively short detection range and high capital and operating cost of air sampling stations, wide-area environmental sampling would be most suitable for detecting undeclared reprocessing activities over limited areas, such as the Middle East.

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[17] The area included parts of Iran, Iraq, Jordan, Kuwait, Saudi Arabia, Syria, and Turkey; for comparison, the total combined area of these counties is about 5.3 million square kilometers. The network of 26 stations was estimated to be able to detect the kryption-85 emissions from a reprocessing facility over 85 percent of the "primary focus area," with a 95 percent or greater probability of detection of at least one weekly release at one station and a 5 percent false alarm rate per release. The "primary focus area" was the 15 percent of the million square kilometer area having roads or railways within 1 kilometer, electrical transmission lines within 10 kilometers, and a population center of 5,000 or more people within 20 kilometers. Doubling these distances would roughly double the primary focus area and the required number of stations.

The IAEA study estimated releases of a mere 0.01 to 1 gram per year of HEU for a centrifuge enrichment facility producing 25 kilograms of HEU per year, based on data from existing commercial facilities. Even at the upper limit of 1 gram per year, the study concluded that a network of 26 stations could detect with high probability releases from a clandestine centrifuge enrichment facility over only a tiny fraction of a million square kilometer area of the Middle East (even after excluding the areas considered too far from roads, electricity, and people to support such a facility).[18] Releases from gaseous diffusion and electromagnetic isotope enrichment plants would be much larger and more detectable. Unless substantial progress is made in reducing the cost or increasing the sensitivity of analyzing uranium particulate samples, wide-area environmental sampling would be a practical method of detecting undeclared uranium enrichment activities only over small areas, such as the Korean peninsula.

In summary, we judge that environmental samples taken during on-site inspections can be highly effective in detecting significant undeclared enrichment or reprocessing activities at declared or suspect facilities. Environmental sampling is less able to detect such activities at unidentified facilities, or to provide assurance that no significant, undeclared enrichment or reprocessing activities have occurred in a particular state. Although reliable detection of clandestine reprocessing appears possible at reasonable cost for at least limited regions (assuming that facility operators do not cryogenically trap krypton emissions), reliable detection of clandestine centrifuge enrichment over large areas currently is not possible at reasonable cost.

On-site Inspections

As discussed in Chapters 2 and 3, routine on-site inspections are vital for confirming declarations of inventories and activities at declared sites. While possibly subject to numerical quotas, such inspections at declared sites should not be subject to refusal by the party being inspected. The inspectors should be guaranteed protection and prompt unimpeded access with any equipment agreed to be necessary for inspection purposes, but agreed limitations on the

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[18] The network of 26 stations was estimated to be able to detect a change in the U-238:U-235 ratio over 2 percent of the primary focus area, with a 95 percent or greater probability of detection of at least one weekly release at one station and a 5 percent false alarm rate per release.

extent of access relating to the protection of sensitive weapons information could be acceptable.

If evidence of suspect activities at undeclared sites has been discovered by some combination of NTM, human intelligence, wide-area environmental sampling, or information developed in the process of routine inspections and audits of declared activities, challenge inspections would provide a mechanism for clarifying the situation. The right to conduct on-site inspections of suspect sites is provided for in the Additional Protocol to the IAEA safeguards agreements, as well as various other multilateral and bilateral arms control treaties.

The modalities of how a challenge inspection would be initiated and conducted would depend on whether an agreement was bilateral or multilateral. An existing example of the mechanism for dealing with such issues is the Joint Compliance and Inspection Commission (JCIC) established by the START I Treaty to resolve questions of compliance. The JCIC and other similar commissions have successfully resolved many issues over the past three decades. In the case of multilateral treaties various procedures have been adopted. In the CTBT, any party can request an on-site inspection for cause but at least 30 of the 51 members of the Executive Committee would have to approve the inspection; in the Chemical Weapons Convention, an inspection would proceed automatically unless it was opposed by a given number of parties. Under the Additional Protocol the IAEA must give notice of inspection at least 24 hours in advance, and give the reasons for the inspection. The rights of inspection are broad, including environmental sampling, radiation surveys, examination of shipping records, visual surveys, and so forth. Protection of "proliferation sensitive information" is provided but this protection must not prevent the agency from collecting credible assurance of the absence of undeclared NEM or of the completeness of the specified declarations.

Two questions are frequently asked about challenge inspections. First, would the United States be willing to call for a challenge inspection when the evidence for the "probable cause" could jeopardize sensitive intelligence sources and methods? Even if the source of the original stimulus for suspicion might in fact be very sensitive, we believe corroborative evidence could be made available and locations could be established using commercial satellite photography, which now has good resolution. Second, would a multilateral Executive Committee be willing to authorize an inspection that could have serious political or military repercussions? Once the United States requested approval from a multinational committee, we believe it should be possible to obtain the necessary support for an inspection when a convincing case could be presented. When necessary, the request could be backed up by sharing relevant classified information privately with other states or publicly as has been done in the past. In practice, the number of challenge inspections for an agreement related to nuclear weapons or NEM should be relatively few. Unless wide-area environmental sampling is used there are no natural events to trigger the system, as is the case with earthquakes in the CTBT.

Finally, there is the question of whether any state would permit an on-site inspection that would prove it was in violation of the agreement. Although the challenged country would probably attempt to block or delay the inspection by various means, the international community would undoubtedly see rejection of a challenge inspection, when a serious case for cause had been presented, as an admission of guilt. If the challenged country were indeed innocent of the charges, the inspection would provide an opportunity to clear itself and possibly shift international criticism to the party calling for the inspection in the first place.

Detection of Nuclear Weapon Programs by U.S. Intelligence

The historical record of U.S. intelligence in identifying foreign nuclear weapon programs is a valuable reference point for evaluating the likelihood that clandestine weapons programs would be detected in the future. At present the record and even some underlying capabilities of U.S. intelligence relating to recent events are the subject of intense controversy. On the specific question of how early the United States became aware of efforts to acquire nuclear weapons, however, the record is good. In every known case, U.S. intelligence became aware of efforts by other countries to develop nuclear weapons relatively early in these programs and well in advance of the actual achievement of a nuclear device. Although there have often been inaccuracies in detailed estimates, such as the date of the initial fabrication of a nuclear device and the total number of weapons assembled as of a given date, the United States has identified key production facilities before a significant amount of NEM or a nuclear weapon was produced. The following is a very brief summary of the U.S. experience:

- **Soviet Union.** Despite extreme secrecy, the existence of the Soviet nuclear weapons program became known soon after World War II, and the facilities that eventually produced the first NEM were identified by 1948. Knowledge of the Soviet program emerged from analysis of many unrelated sources ranging from very sensitive NTM to the open literature, which taken together pointed unambiguously to a high-priority project to develop nuclear weapons as rapidly as possible.[19] The Soviet Union conducted its first nuclear test sooner than most analysts anticipated, but the purpose and general nature of the program were clear well before the first Soviet test in late August 1949.[20]

- **China.** U.S. intelligence identified all of China's major NEM production facilities prior to their operation.[21] Limited to the use of satellite and aerial photoreconnaissance by the strict secrecy of Maoist China, U.S. intelligence had difficulty in determining the operational status and capacity of these facilities. Although U.S. intelligence correctly identified the uranium enrichment facility at Lanzhou two years before China tested its first weapon (which used HEU produced by this facility), for example, it underestimated the capacity of the plant and judged that the facility would not be operational for three more years.[22]

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[19] Nuclear History Program, Berlin Crisis History Session #8, Interview with Spurgeon M. Keeny, Jr., October 30, 1992, Transcript. Center for International Security Studies at the School of Public Affairs, University of Maryland, pp. 320-321 and Henry S. Lowenhaupt, "On the Soviet Nuclear Scent," *Studies in Intelligence*, Central Intelligence Agency, Fall 1967, pp.13-29. Secret document, declassified and approved for release.

[20] Roscoe H. Hillenkoetter, "Estimate of the Status of the Russian Atomic Energy Project," Director of Central Intelligence Memorandum to the President, July 6, 1948, p. 1, and David Holloway, *Stalin and the Bomb: The Soviet Union and Atomic Energy* (New Haven, CT: Yale University Press, 1994), p. 220.

[21] National Intelligence Estimate [NIE] 13-2-60, "The Chinese Communist Atomic Energy Program," December 13, 1960; National Intelligence Estimate [NIE] 13-2-62, "Chinese Communist Advanced Weapons Capabilities," April 25, 1962; Special National Intelligence Estimate [SNIE] 13-2-63, "Communist China's Advanced Weapons Program," July 24, 1963; Special National Intelligence Estimate [SNIE] 13-4-64, "The Chances of an Imminent Chinese Communist Nuclear Explosion," August 26, 1964; and National Intelligence Estimate [NIE] 13-2-65, "Communist China's Advanced Weapons Program," January 27, 1965. All partially declassified, approved for release and available as of January 2005, at: http://nsarchive.chadwyck.com.

[22] National Intelligence Estimate [NIE] 13-2-62, "We believe that the Chinese would at some point in their program endeavor to produce U-235, but we have no evidence of U-235 production at present. Latest evidence indicates that a facility at Lanchou [Lanzhou] suspected of being a gaseous

- **Israel.** The United States photographed what was to become the Dimona nuclear facility under construction in the late 1950s,[23] and the existence of a plutonium production reactor at the site was clearly established in the early 1960s.[24] Any doubts about the purpose of the program[25] were removed when Israel refused to allow the United States to carry out meaningful bilaterally agreed inspections of Dimona.[26]
- **India.** India's nuclear test in 1974 came as a surprise,[27] but the suspicious nature of the secretive Indian nuclear program was recognized a number of years earlier and the facilities supporting the development of the device had been identified.[28]

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diffusion plant has not been completed. If this plant is in fact intended to be a gaseous diffusion facility, it probably could not produce weapon grade U-235 before 1965. The Chinese could probably test an all U-235 or composite device within a year after the activation of a production facility," p. 4.

[23] Avner Cohen, *Israel and the Bomb* (New York, NY: Columbia University Press, 1998), p. 83.

[24] Dean Rusk to John F. Kennedy, "Israel's Atomic Energy Activities," Department of State Memorandum, January 30, 1961, p. 1. Secret document, partially declassified and approved for release. Available as of January 2005, at: http://nsarchive.chadwyck.com.

[25] William N. Dale to Department of State, "Current Status of the Dimona Reactor," Department of State Airgram A-742, April 9, 1965, p. 5. Secret document, partially declassified and approved for release. Available as of January 2005, at: http://nsarchive.chadwyck.com.

[26] From 1961 until 1969, U. S. scientists conducted regular (roughly annual) inspections of Dimona. From the start, the Israelis denied access to most of the key areas in the facility. After the July 12, 1969, inspection, the U.S. and Israeli governments reached an agreement to discontinue the procedure. See Avner Cohen, *Israel and the Bomb* (New York, NY: Columbia University Press, 1998), pp. 329-338 and Memorandum of Conversation, "1969 Dimona Visit," Department of State, August 13, 1969, p. 2. Secret document, declassified and approved for release. Available as of January 2005, at: http://www2.gwu.edu/~nsarchiv/israel/documents/visit/01-01.htm.

[27] The U.S. intelligence community did not detect the preparation for the May 18, 1974, "peaceful nuclear explosion" at the Thar Desert test site near the city of Pokhran prior to the test but were well aware that India possessed a capability to test at any time. See National Security Study Memorandum [NSSM] 156, "Indian Nuclear Developments," September 11, 1972, p. 1. Secret document, partially declassified and approved for release. Available as of January 2005, at: http://nsarchive.chadwyck.com.

[28] George McGhee to Dean Rusk, "Anticipatory Action Pending Chinese Communist Demonstration of Nuclear Capability," Department of State, September 13, 1961. Available as of January 2005, at: http://nsarchive.chadwyck.com. "India's atomic program is sufficiently advanced so that it could, not many months hence, have accumulated enough fissionable material to produce a nuclear explosion," p. 2 and George Perkovich, *India's Nuclear Bomb: The Impact on Global Proliferation* (Berkeley, CA: University of California Press, 1999), p. 52.

- **Pakistan.** The fact that Pakistan was engaged in a major effort to develop nuclear weapons was apparent in the mid-1970s, early in the program.[29] The location and nature of the facilities supporting the effort were also identified early, including the secret uranium enrichment facility at Kahuta. In response to Pakistan's covert theft of Urenco centrifuge enrichment technology,[30] the United States terminated economic and military aid to Pakistan in 1977 and again in 1979, many years before Pakistan was able to produce significant amounts of HEU and assemble its first weapon.[31]
- **South Africa.** The goals of the South African nuclear program were long suspect, particularly when in the 1970s South Africa developed the Helikon enrichment process capable of producing HEU.[32] The United States cut off nuclear cooperation in 1976 due to South Africa's refusal to sign the NPT. These suspicions were confirmed in 1977 when the United States was informed by the Soviet Union that one of its satellites had discovered an apparent nuclear test site in the Kalahari Desert.[33]

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[29] National Security Study Memorandum [NSSM] 202, "U.S. Non-proliferation Policy," May 23, 1974, p. V-9. Secret document, partially declassified and approved for release. Available as of January 2005, at: http://nsarchive.chadwyck.com and Swarts to Hartman, "Demarche to Pakistan on Nuclear Fuel Reprocessing," Department of State, January 30, 1976, p. 1. Secret document, partially declassified and approved for release. Available as of January 2005, at: http://nsarchive.chadwyck.com.

[30] State Department Briefing Paper, "The Pakistani Nuclear Program," June 23, 1983, p. 4. Secret document, partially declassified and approved for release. Available as of January 2005, at: http://nsarchive.chadwyck.com.

[31] *Tracking Nuclear Proliferation, 1998: Pakistan*, "Glenn-Symington Amendment" (Washington, DC: Carnegie Endowment for International Peace, 1998). Available as of January 2005, at: http://www.ceip.org/files/Publications/TrackingPakistan.asp.

[32] Directorate of Intelligence, "Prospects for Further Proliferation of Nuclear Weapons," October 2, 1974, p. 5. Classified memorandum partially declassified and approved for release. Available as of January 2005, at http://nsarchive.chadwyck.com and Directorate of Intelligence, "New Information on South Africa's Nuclear Program and South African-Israeli Nuclear and Military Cooperation," March 30, 1983, p. 1. Secret document, partially declassified and approved for release. Available as of January 2005, at: http://www.foia.ucia.gov.

[33] David Albright, "South Africa's Secret Nuclear Weapons," *ISIS Report* (Washington, DC: Institute for Science and International Security, May 1994). Available as of January 2005, at:

- **Iraq.** Iraq's nuclear program became the object of suspicion beginning in the late 1970s. Israel was sufficiently concerned about the ultimate purpose of the Osiraq research reactor that in 1981 it destroyed the reactor in a controversial bombing raid. There was considerable evidence of the buildup of the Iraqi nuclear program during the 1980s, and key facilities were identified and destroyed during the 1991 Gulf War.[34] Subsequent inspections determined that the nuclear program, while more extensive than previously believed, had not produced a weapon or significant amounts of NEM.
- **North Korea.** North Korea became the subject of suspicion when it began construction in the early 1980s of a small graphite-moderated reactor capable of producing significant quantities of plutonium.[35] Although North Korea signed the NPT in 1985, this suspicion grew when it delayed signing the required IAEA inspection protocol until 1992. During this period North Korea initiated construction of much larger graphite-moderated nuclear reactors, as well as a building identified by U.S. intelligence as a suspected reprocessing facility,[36] and a suspected site where associated reproc-

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http://www.isis-online.org/publications/southafrica/ir0594.html and Mitchell Reiss, "South Africa: Castles in the Air," in *Bridled Ambition: Why Countries Constrain Their Nuclear Capabilities* (Washington, DC: Woodrow Wilson Center, 1995), p. 10.

[34] Iraq had three operating reactors including the Osiraq reactor. Two small research reactors, IRT 5000 rated at 5,000 kilowatts and Tammuz 2, rated at 500 kilowatts, were both damaged by Coalition air strikes in March 1991. See Iraq Profile, "Iraqi Nuclear Facilities: Research Reactors," *The Nuclear Threat Initiative*, Available as of January 2005, at: http://www.nti.org/e_research/profiles/Iraq/Nuclear/2117_3362.html.

[35] Gary Samore, ed. *North Korea's Weapons Programmes: A Net Assessment, An IISS Strategic Dossier* (Basingstoke, UK and New York, NY: International Institute for Strategic Studies and Palgrave Macmillan, 2004). "Through satellite reconnaissance, the US detected the construction of the 5MW(e) reactor at an early stage, and was able to confirm initial operation of the reactor in 1986 by noting the emission of steam plumes from its cooling tower, which indicated the reactor was venting excess heat," p. 35. See also Michael J. Mazarr, *North Korea and the Bomb: A Case Study in Nonproliferation* (New York, NY: St. Martin's Press, 1995), p. 40.

[36] Gary Samore, ed. *North Korea's Weapons Programmes: A Net Assessment, An IISS Strategic Dossier* (Basingstoke, UK and New York, NY: International Institute for Strategic Studies and Palgrave Macmillan, 2004), p. 36. In July 1989, the U.S. media described a U.S. and South Korea meeting on the suspected North Korean reprocessing facility at Yongbyon, corroborating earlier South Korean media reports. See, for example, John J. Fialka, "North Korea May Be Developing Ability to

essing wastes were hidden. The first IAEA inspections of the facility in 1992 and 1993 confirmed U.S. suspicions that plutonium had been separated from irradiated reactor fuel.[37]

- **Iran.** Iran received significant assistance from China for its civilian nuclear program beginning in the mid-1980s, and in 1995 Iran contracted with Russia to complete one of the two partially constructed reactors at Bushehr, which were begun with German assistance in the late 1970s but were severely damaged during the 1980-1988 Iran-Iraq War. The United States pressed China and Russia throughout the 1990s to curtail their nuclear cooperation with Iran, citing intelligence information indicating that Iran intended to develop nuclear weapons. Evidence of a secret centrifuge enrichment program began to emerge publicly as early as 1995, and in August 2002 the existence of a secret nuclear facility at Natanz was revealed by an Iranian opposition group.[38] Perhaps in response to these leaks, in 2003 Iran opened what it claimed to be all of its facilities to IAEA inspection, including a pilot centrifuge enrichment plant under construction near Natanz.[39] The controversy over Iran's nuclear program continues, but the relevant point here is that the existence of the NEM production program was discovered well before weapons or significant amounts of HEU were produced.

Build Nuclear Weapons," *The Wall Street Journal*, July 19, 1989, p. A16, and Don Oberdorfer, "North Koreans Pursue Nuclear Arms: U.S. Team Briefs South Korea on New Satellite Intelligence," *The Washington Post*, July 29, 1989, p. A9.

[37] Michael J. Mazarr, *North Korea and the Bomb: A Case Study in Nonproliferation* (New York, NY: St. Martin's Press, 1995), p. 84. For additional details see: Samore, *North Korea's Weapons Programmes*, "The 1992 Plutonium Mystery," pp. 36-38.

[38] News Bulletin, "Mullahs' Top Secret Nuclear Sites and Weapons of Mass Destruction Projects," *Iran Liberation*, The National Council of Resistance of Iran, August 19, 2004, p. 2. Available as of January 2005, at: http://www.globalsecurity.org/wmd/library/news/iran/2002/iran-020819-ncri_news.pdf.

[39] Mohamed ElBaradei, "Implementation of the NPT Safeguards Agreement in the Islamic Republic of Iran," Report by the Director General, November 10, 2003 (Derestricted November 26, 2004). Available as of January 2005, at: http://www.iaea.or.at/Publications/Documents/Board/2003/gov2003-75.pdf.

- **Libya.** Libya was long believed to have been laying the groundwork for a nuclear weapons program. Under pressure from the United States and the United Kingdom, Libya disclosed details of this effort at the beginning of 2004, took steps to terminate it, and agreed to accede to the Additional Protocol to the IAEA safeguards agreement.[40] Although it had received substantial assistance, the Libyan program had not progressed to the point of producing NEM.
- **Other Programs.** In the past a number of other states, including Argentina, Brazil, South Korea, Taiwan, Switzerland, and Sweden, initiated programs directed at developing a nuclear weapon capability. All of these programs were subsequently abandoned when the political leadership recognized that the programs would not be in the overall best interests of those states. In each of these cases, the United States had early indications of the evolving plans, which allowed high-level diplomacy to influence political leaders, who in some cases may not have been fully aware of the actions of secret organizations within their own military and scientific communities.

Looking ahead, the technical collection capabilities of U.S. intelligence will continue to increase, as they have over the last half century, particularly with the advent of advanced space-based sensor technology. Although substantial uncertainties have and will continue to surround intelligence estimates, it is important to remember that in the context of an international agreement in which all nuclear facilities were declared, these uncertainties could be resolved by requesting an on-site inspection of the suspect facility. As noted in the previous section on environmental monitoring, an on-site inspection would be highly likely to detect any significant undeclared activities, such as the enrichment of uranium or the separation of plutonium. Based on the historical evidence, and with these additional capabilities, we judge that a clandestine nuclear weapons program very likely would not escape early detection.

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[40] Mohamed ElBaradei, "Implementation of the NPT Safeguards Agreement of the Socialist People's Libyan Arab Jamahiriya," Report by the Director General. May 28, 2004. Available as of January 2005, at: http://www.fas.org/nuke/guide/libya/iaea0504.pdf.

CONCLUSIONS

As discussed in Chapters 2 and 3, procedures and technology are available to verify with high confidence the declarations of stockpiles of nuclear weapons and NEM at declared sites. Independent knowledge of the actual total size of the Russian stockpiles of nuclear weapons and NEM, however, is sufficiently uncertain that verified declarations alone cannot preclude the possibility that undeclared stockpiles might exist at undeclared locations. Although there is a good chance that the possible existence of undeclared stockpiles would be revealed by a combination of National Technical Means, human intelligence, audits of records, and physical inventories, the theoretical possibility that significant numbers of undeclared weapons had been retained at hidden sites would remain for many years, and perhaps several decades.

Undeclared nuclear weapons also could come into existence by the clandestine production of NEM. Past experience indicates a high probability that this would be detected over time. Though not perfect, NTM, human sources, and environmental monitoring form a fairly tight net with which to catch evidence of the large programs and facilities required to produce NEM. Given the extensive knowledge of existing nuclear programs, the massive amounts of additional information that would result from the process of verifying declarations, the new inspection capabilities provided by the IAEA Additional Protocol, and the demonstrated capabilities of NTM, it is very unlikely that any state, including Russia, participating in a cooperative fashion involving detailed declarations could develop a complete, stand-alone covert nuclear weapon production program that would not be discovered over time. If, however, undeclared stocks of NEM exist or can be diverted without detection from civilian stocks or production facilities, it is much more likely that the assembly of new weapons could escape detection.

The synergistic effect of the approaches discussed in Chapters 2, 3, and 4 in a cooperative environment, coupled with robust NTM capabilities, would substantially reduce current uncertainties in U.S. assessments of foreign nuclear weapon and NEM stockpiles over time. Nevertheless, in view of the sheer size and age of the Russian stockpile (where current uncertainties amount to the equivalent of several thousand weapons), Russia probably could conceal undeclared stocks equivalent to several hundred weapons. In the case of other countries with much smaller programs, absolute uncertainties would be much less, leading to the possibility that these countries could conceal undeclared stocks equivalent to one or two dozen weapons in the case of China, and at most one or two weapons in the case Israel, India, and Pakistan. Confidence that declarations were accurate and complete, and that covert stockpiles or production facilities did not exist, would be increased by the successful operation of a monitoring program over a period of years in an environment of increased transparency and cooperation.

5

General Conclusions

This study has examined the contributions that current and improved transparency and monitoring could make to verification for all categories of nuclear weapons and their nuclear-explosive components and for nuclear-explosive materials (NEM). Chapter 1 described the goals, context, and historical background for such an assessment. The next two chapters explored the capabilities and limitations of a variety of technical and institutional approaches to the pursuit of transparency and monitoring for nuclear weapons and components (Chapter 2) and NEM (Chapter 3) in a cooperative international environment. Chapter 4 then addressed the special challenges of dealing with noncooperation in the form of retention of undeclared stocks and clandestine production of nuclear weapons and NEM and how cooperation could be used to reduce uncertainties about compliance.

As we stated at the outset, the fundamental motivation for this study was to assess whether and how currently available and foreseeable technologies and processes for transparency and monitoring could support the urgent and interrelated goals of reducing the dangers from existing nuclear arsenals, minimizing the spread of nuclear weaponry to additional states, and preventing the acquisition of nuclear weapons by terrorists. The transparency and monitoring technologies and processes we examined could be applied in connection with a variety of approaches to reducing these dangers, including limitations on quantities of nuclear weapons and NEM, limitations on stocks and production of NEM and disposal of excess material, and programs of national protection, control, and accounting for weapons, weapon components, and NEM. We note that increased multinational transparency and cooperative monitoring may also be applied as an approach in its own right, particularly but not solely for reassurance and confidence building.

As discussed in detail in Chapters 2 through 4, providing assurance of the size, character, and status of stocks of nuclear weapons, nuclear weapon components, and NEM to parties other than their possessors generally entails (1) *declarations* and access to supplementary information provided by the possessors to the other parties, (2) additional forms of *transparency* provided by the possessors, and (3) various types of *monitoring* by which the other parties can confirm that the declarations are correct and complete. This basic architecture for verification built upon transparency and monitoring applies whether the focus is a few containers of nuclear-explosive material or an extensive nuclear stockpile containing thousands of intact weapons and components and many tons of NEM.

Interest in the possible benefits of increased transparency and monitoring has long been limited by two widely held suppositions. The first is that it is simply not technically feasible under present and foreseeable circumstances to verify numbers of nuclear weapons themselves (as opposed to number of delivery systems)—and even less to verify stockpiles of NEM. The second is that any attempt to address the difficulty of significantly increasing transparency about nuclear weapons and NEM would necessarily collide with critical national security needs to protect nuclear weapon secrets. We have attempted in this study to understand and clarify the extent to which these suppositions are in fact valid. We have done so by assessing the challenges for transparency and monitoring for the numbers and status of nuclear weapons and quantities of NEM, the state of the art in technological and institutional approaches for addressing these challenges, and the prospects for improving the state of the art—not only through creating new technologies but also through combining existing technological and institutional capabilities more effectively.

As a result of this assessment we have come to the following general conclusions:

1. Current and foreseeable technological capabilities exist to support verification at declared sites, based on transparency and monitoring, of declared stocks of all categories of nuclear weapons—strategic and nonstrategic, deployed and nondeployed—as well as for the nuclear-explosive components and materials that are their essential ingredients. Many of these capabilities could be applied in existing bilateral and international arrangements without the need for additional agreements beyond those currently in force.
2. There are some tensions between sharing information about nuclear weapon and NEM stockpiles and maintaining the security of these stockpiles, but cooperative use of available and foreseeable technologies can substantially alleviate these tensions.
3. The nature of NEM production and the characteristics of NEM and nuclear weapons place some fundamental limits

on the capabilities of any system of monitoring and transparency to provide assurance of compliance; accordingly, a degree of uncertainty is inescapable.

4. The biggest challenge to the kinds of cooperation-based verification discussed here would arise if countries tried to give the appearance of cooperation while covertly retaining undeclared stockpiles of nuclear weapons or NEM and/or undertaking clandestine production programs. Where concerns about compliance exist, the synergistic effect of multiple technical and management measures, supported by increased transparency and robust national technical means of intelligence collection, could reduce the risk that significant clandestine activities would go undetected and over time could build confidence that verification was effective.
5. Important transparency measures for both nuclear weapons and NEM need not necessarily be imposed as part of formal treaties but could be undertaken on the basis of informal understandings or unilateral initiatives, for example as part of broader confidence-building efforts.
6. There are both liabilities and benefits of seeking, in the long run, to incorporate measures governing transparency and monitoring of nuclear weapon and NEM stockpiles into formal agreements. The complexity and intrusiveness of the most ambitious measures mean that negotiation of such agreements may be difficult and protracted. But it is precisely the complexity and intrusiveness of some of the relevant measures that, together with the national security stakes, make formal agreements useful to avoid misunderstandings and to provide mechanisms to clarify ambiguities. In addition, formal agreements provide more durable assurance that measures will be sustained over time and across changes in governmental leadership.
7. In the committee's judgment, the synergistic effect of the approaches discussed in Chapters 2, 3, and 4 in a cooperative environment, coupled with robust NTM capabilities, would substantially reduce current uncertainties in U.S. assessments of foreign nuclear weapon and NEM stockpiles over time. Nevertheless, in view of the sheer size and age of the Russian stockpile (where current uncertainties amount to the equivalent of several thousand weapons), Russia probably could conceal undeclared stocks equivalent to several hundred weapons. In the case of other coun-

tries with much smaller programs, absolute uncertainties would be much less, leading to the possibility that these countries could conceal undeclared stocks equivalent to one or two dozen weapons in the case of China, and at most one or two weapons in the cases of Israel, India, and Pakistan. Confidence that declarations were accurate and complete, and that covert stockpiles or production facilities did not exist, would be increased by the successful operation of a monitoring program over a period of years in an environment of increased transparency and cooperation.

Appendix A

Physics and Technology of Nuclear-Explosive Materials

NEM and Fissile Materials

Nuclear weapons exploit the explosive release of nuclear energy from an exponentially growing chain reaction sustained by fissions triggered by “fast” neutrons (i.e., neutrons of energy in the thousands of electron-volts). Nuclides that are capable of supporting a chain reaction of this kind when present in suitable quantity, purity, and geometry are called “nuclear-explosive nuclides.” Any mixture of nuclear-explosive and other nuclides that can be made to support such a chain reaction when present in suitable quantity, purity, and geometry is called “nuclear-explosive material” (NEM). The most important nuclear-explosive nuclides are listed in Table A-1.

The term “fissile” refers to nuclides that can sustain a chain reaction under circumstances in which emitted neutrons are thermalized (i.e., slowed down to velocities corresponding to the temperature of the surroundings) before inducing further fissions. (This property is essential to the operation of the thermal-neutron reactors that have accounted for most nuclear electricity generation, nuclear naval propulsion, and weapon plutonium production around the world.) The underlying physics is such that all fissile nuclides are also nuclear explosives, but not all nuclear-explosive nuclides are fissile; for example, the even-numbered isotopes of plutonium—most importantly Pu-238, Pu-240, and Pu-242—are not fissile, but they are nuclear explosives.

Reactivity, Critical Mass, and Explosive Yield

TABLE A-1 Properties of Nuclear-Explosive Nuclides

Isotope or Mixture	Critical Mass (kg)	Half Life (years)	Decay Heat (watts/kg)	Neutron Production From Spontaneous Fission (per kg-sec)	Main Gamma Energies (MeV)
U-233	16	160,000	0.28	1.2	2.6 from Tl-208
U-235	48	700,000,000	0.00006	0.36	0.19
Np-237	59	2,100,000	0.021	0.14	0.087
Pu-238	10	88	560	2,700,000	0.100
Pu-239	10	24,000	2.0	22	0.41
Pu-240	37	6,600	7.0	1,000,000	0.10
Pu-241	13	14	6.4	49	0.66 from Am-241
Pu-242	89	380,000	0.12	1,700,000	0.045
Am-241	57	430	110	1,500	0.66

The critical masses given are for a bare sphere of metal at normal density. Plutonium metal can exist in six different forms corresponding to different crystalline configurations, with different densities. The two of these that are most germane for nuclear weapons are alpha phase (density 19.6 grams per cubic centimeter) and delta phase (density 15.7 grams per cubic centimeter). The indicated critical masses are for alpha-phase plutonium. For delta-phase plutonium, the critical masses would be about 60 percent larger. In the case of Pu-239, neutron production is 22/kg-sec from spontaneous fission but 630/kg-sec from alpha-n reactions. In Pu-238, alpha-n reactions add 200,000/kg-sec to the 2,700,000/g-sec produced by spontaneous fission. In the other cases, augmentation by alpha-n reactions is not significant.

Adapted from: Nuclear Energy Research Advisory Committee, *Attributes of Proliferation Resistance for Civilian Nuclear Power Systems*, U.S. Department of Energy, October 2000; General Electric, *Nuclides and Isotopes*, 14th ed., 1989.

The nuclear reactivity of any nuclear-explosive nuclide or mixture of such nuclides depends on the cross sections (reaction probabilities) of the relevant nuclides for induced fission by incident neutrons of various energies and, alternatively, for absorbing such neutrons without fissioning. The reactivity also depends on the geometries, densities, and chemical forms in which the nuclear-explosive nuclides are present, and whether and to what extent the elements or compounds containing the nuclear-explosive isotopes are diluted or contaminated with other nuclides and compounds that can slow or absorb neutrons.

A nuclear explosion is achieved by the rapid assembly, in a suitable geometry, of NEM embodying sufficient nuclear reactivity to initiate and sustain a chain reaction driven by fast neutrons. This means that, on the average, at least one of the several energetic neutrons released per fission will be "productively" captured by another nuclear-explosive nuclide—before the neutron escapes, is unproductively captured, or slows down—resulting in another fission. If that condition is met in a way such that each fission causes exactly one additional one, the configuration is said to be "critical;" if each fission causes more than one additional fission, the configuration is "supercritical."

The mass of NEM required to reach criticality if the material is in the form of a solid sphere at normal density in free space (i.e., not surrounded by material that can reflect neutrons) is called the "bare-sphere critical mass." Table A-1 gives the bare-sphere critical masses for the most significant nuclear-explosive nuclides, along with some other properties that bear on the attractiveness of the nuclides as weapon material, namely,

- the radioactive half-life (longer is better for weapons use, inasmuch as shorter half-lives imply more rapid transformation of the nuclear-explosive nuclide into something else, the buildup of which may ultimately change the explosive properties of the material);[1]
- the rate of heat generation by radioactive decay; high rates of heat generation can accelerate deterioration and/or internal distortion of weapon components if the heat is not removed by appropriate design.
- the rate of neutron production by spontaneous fission and reactions with alpha particles emitted in radioactive decay; the emission of neutrons by these processes may pre-initiate a chain reaction earlier in the process of assembling a nuclear weapon than is optimal.
- the energies of the gamma rays emitted by radioactive decay of the nuclide or its progeny; energetic gamma rays are difficult to shield and therefore tend to lead both to detectable signals and to radiation doses to people handling NEM or weapons.

The nuclides whose properties are tabulated in Table A-1 form the basis of the diverse grades of nuclear materials listed with their properties in Table A-2.

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[1] All nuclear-explosive nuclides are also radioactive. Most radioactive nuclides, however, are not nuclear explosives.

TABLE A-2 Heat, Radioactivity and Radiation from Various Nuclear Materials

Material	Radioactivity (Ci/g)	Neutron Generation (n/g-sec)	Heat Release (W/kg)	Gamma Dose (rem/hr)
Natural U	0.0000007	0.013	0.000019	0.000012
LEU	0.0000019	0.012	0.000054	0.000057
Weapon-grade HEU	0.0000095	0.0014	0.00026	0.0015
Weapon-Grade Pu	0.22	52	2.5	0.94
Reactor-Grade Pu	6.2	340	14	15

Compositions (percentage by weight) of the indicated materials are assumed to be as follows:

Natural U = 99.275 percent U-238, 0.7193 percent U-235, 0.0057 percent U-234
LEU (Low Enriched Uranium) = 96.475 percent U-238, 3.5 percent U-235, 0.025 percent U-234
HEU (Highly Enriched Uranium) = 5.88 percent U-238, 94.0 percent U-235, 0.12 percent U-234
Weapon Pu = 0.01 percent Pu-238, 93.8 percent Pu-239, 5.8 percent Pu-240, 0.13 percent Pu-241, 0.02 percent Pu-242, 0.22 percent Am-241
Reactor Pu = 1.3 percent Pu-238, 60.3 percent Pu-239, 24.3 percent Pu-240, 5.6 percent Pu-241, 5.0 percent Pu-242, 3.5 percent Am-241

The gamma-ray dose is calculated at the surface of a sphere of the metal with a mass of a few kilograms. Abbreviations: Ci = curie, g = gram, kg = kilogram, m^3 = cubic meter, n = neutrons, W = watt.

A nuclear weapon contains NEM stored in a subcritical configuration. Detonation of the weapon then requires that the NEM be rapidly assembled into a supercritical configuration, wherein the chain reaction grows almost instantaneously to explosive proportions. The explosion ceases once the unreacted part of the NEM has been sufficiently dispersed by the pressures resulting from the energy release (or the thermal expansion in case of a very modest supercriticality) to make the configuration again subcritical.

Assembly can be effected either by rapidly joining two subcritical NEM components into a supercritical state (this is the principle of a gun-type weapon) or by rapidly compressing a subcritical NEM component to supercriticality (the implosion type weapon). In a gun-type weapon, a subcritical piece of NEM is propelled by chemical explosives into another subcritical piece of NEM; this process takes several milliseconds. In an implosion device, the NEM component—called a “pit”—is surrounded by chemical explosive lenses, the convergent implosion from which can compress the pit in a fraction of a millisecond.

The reason highly enriched uranium (HEU) can be used in gun-type weapons, while plutonium cannot, is that the high rate of spontaneous neutron emission by all plutonium isotopes invariably pre-initiates the chain reaction, given the relatively slow rate of assembly of a critical mass achievable in a gun-type device. The more rapid implosion alternative to a gun-type design overcomes this pre-initiation liability of plutonium.

The implosion approach can be effective enough in overcoming the problem of a high spontaneous rate of neutron generation to cope with even the extremely high neutron production rates associated with Pu-238, Pu-240, and Pu-242. Therefore plutonium of virtually any isotopic composition can be used in implosion weapons. Indeed, with sufficient sophistication in design and manufacturing, the less desirable mixtures of isotopes (such as the mixture in reactor-grade plutonium) can be used to make nuclear weapons with performance very similar to what is achievable with weapon-grade plutonium.[2]

For potential weapon makers with limited relevant knowledge and technical skills, however, the gun-type approach using HEU is a great advantage, since design and implementation are much simpler for gun-type than for implosion-type weapons. HEU has the further advantages of only weak radioactivity and negligible heat generation. Indeed, the gamma dose rates and radiological hazards from uranium at all levels of enrichment in U-235 are so low that radiation exposure is a negligible consideration for anyone stealing it or trying to make a weapon from it. Plutonium of any isotopic composition has a higher rate of heat generation than does HEU, and plutonium metal itself is more hazardous radiologically—and in other ways more difficult to work with—than HEU is. The difficulties of heat generation and radiological hazard are larger for reactor-grade plutonium than for weapon-grade plutonium, although these problems are by no means insurmountable.

The critical mass can be made smaller than the bare-sphere value by surrounding the nuclear-explosive material with a "tamper" composed of materials that reflect neutrons. Note also that the implosion approach compresses the NEM to higher than normal density, thereby also reducing the critical mass. The reduction available from use of a reflector is in the range of factor of two or

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[2] See, e.g., U.S. DOE, Office of Arms Control and Nonproliferation, *Final Nonproliferation and Arms Control Assessment of Weapons-Usable Fissile Material Storage and Excess Plutonium Disposition Alternatives* (Washington, DC: Department of Energy, January 1997), which states at pp. 38-39: "[A]dvanced nuclear-weapon states such as the United States and Russia, using modern designs, could produce weapons from reactor-grade plutonium having reliable explosive yields, weight, and other characteristics generally comparable to those of weapons made from weapon-grade plutonium."

so. As for compression, the critical mass decreases with the square of the material density. Therefore, if it were possible to compress the nuclear-explosive material to twice its normal density the critical mass would decrease by a factor of four. Thus, a nuclear fission weapon might use a considerably smaller amount of nuclear-explosive material than the bare-sphere critical mass.

The metallic forms of the relevant elements give the smallest critical-mass values and produce the most efficient weapons in terms of the fraction of the heavy nuclei present that actually fission. Other chemical forms may also be usable in a nuclear weapon: plutonium oxide, for example, with a bare-sphere critical mass about five times larger than that of plutonium metal, can be made to produce a nuclear explosion.

The explosive yield (i.e., the release of energy) from a nuclear weapon is measured by convention by the corresponding quantity of the chemical high explosive, TNT. The explosion of one metric ton (1,000 kilograms) of TNT releases approximately 1 billion calories[3] of energy, and the corresponding unit of measure ("one ton of TNT equivalent") is defined as exactly 1 billion calories, or 4.2 billion joules.

The first three nuclear weapons (the one tested at Alamogordo, New Mexico, in July 1945 and those dropped on Hiroshima and Nagasaki the following month) had yields in the range of 10 to 20 kilotons (10,000 to 20,000 tons) of TNT. Early efforts by proliferating states are likely to aim for the same range, as would the sorts of designs likely to be tried by terrorists. Fission weapons of more advanced design have involved a range of yields from a fraction of a kiloton to about 500 kilotons; thermonuclear weapons, combining fission and fusion processes may have yields extending into the multimegaton range.

Production Technologies for NEM

Here we review briefly what is entailed in producing the two most important classes of NEM, namely, highly enriched uranium and separated plutonium.

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[3] This is the "small" calorie (i.e., the heat required to increase the temperature of 1 gram of water by 1 degree C), not the "large," or kilocalorie, used in specifying food consumption, which is 1,000 times larger.

Highly Enriched Uranium

The most commonly mined uranium bearing ores today are sandstones in which uranium occurs at concentrations of 0.03 percent to 0.2 percent by weight. Uranium is also found at concentrations on the order of 10 times lower in rather widely distributed shales, and at concentrations a few times lower still in even more widely occurring granites. Depending on the characteristics of the particular geologic formation, such uranium-bearing rocks may be extracted from underground mines or from open pits.[4]

Next the ore is crushed and leached with acid, which dissolves the uranium. It is then extracted as an oxide, U_3O_8. The extraction of uranium from ore is called ”uranium milling,” and the mildly radioactive, sand-like residues of the process are referred to as “uranium mill tailings.” Uranium mining and milling at a scale adequate to support a nuclear weapon program entail sizable and distinctive operations.

The actual process of enriching the U-235 concentration above its value of 0.7 percent in natural uranium is even more demanding. Because different isotopes of uranium behave chemically almost identically, almost all separation methods have relied on physical means of separation, based on the 1.3 percent difference in mass between U-235 and U-238 atoms. In most approaches to this task the natural uranium is first converted to uranium hexafluoride gas (UF_6), followed by physical separation of the lighter U-$235F_6$ molecules from the slightly heavier U-$238F_6$ molecules. The best-known technologies for accomplishing this separation are:

- gaseous diffusion plants, which exploit the difference in the diffusion rates of the lighter and heavier molecules through a “cascade” of thousands of porous barriers; or
- centrifuge plants, which use sets of hundreds or thousands of sophisticated, ultra-high-speed, gas-centrifuge machines to separate the molecules based on their differing inertial masses.

Gaseous diffusion requires large factories containing complex piping arrangements and highly specialized membranes (the characteristics of which remain classified), and utilizes immense

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[4] Uranium also exists in seawater, at the concentration of about 3 parts per billion by weight. This means that a technology capable of extracting half the uranium from a given volume of seawater would need to process about 650,000 cubic meters of water to extract one kilogram of uranium. The means of doing this by selective absorption have been demonstrated on a small scale.

amounts of electric power to run the compressors that force the uranium hexafluoride gas through the membranes. Centrifuge plants have electric power requirements 20-30 times smaller than those of gaseous diffusion plants, but the technology for the centrifuges is extremely demanding. Gas centrifuge plants can be considerably smaller than gaseous diffusion plants, but they still need room for many hundreds or thousands of centrifuges, so concealment poses some challenges.

The gaseous diffusion and centrifuge plants operated for civilian nuclear power enrich uranium only to the 3 to 5 percent U-235 level, unsuitable for nuclear weapons. In terms of the “enrichment work” needed to separate isotopes, however, this concentration is half way or more toward the enrichment levels of 90 percent or greater that are desirable for nuclear weapons. In principle, any of the commercial enrichment plants could be operated in a manner to do the remaining work needed to bring this low enriched reactor fuel up to weapon-usable levels (see Box A-1).

Other approaches to uranium enrichment besides gaseous diffusion and centrifuges have been utilized from time to time. Some have even larger power requirements than those of gaseous diffusion; the Helikon technology used by South Africa and the electromagnetic separation technology, which was developed by the United States during World War II and subsequently pursued by Iraq in its nuclear weapon program, both fall into this category. Others have very low separation factors and thus need a huge number of stages to reach high enrichment; chemically based processes that have been explored by France, Japan, and also by Iraq fall into this category.

Technologies exploiting the capability of precisely tuned lasers to selectively excite U-235 atoms or molecules containing U-235, allowing their separation from the U-238 atoms or molecules containing U-238 by electromagnetic or other means, appear to have the potential for low energy requirements and high separation factors. These technologies have not yet been developed as practical options, however, and it remains unclear whether they might eventually make possible the production of HEU with modest resources and easier concealment.

Separated Plutonium

Any nuclear reactor that contains U-238 in its fuel produces Pu-239 as a result of the absorption of a fission neutron by a U-238 atom and its subsequent radioactive decay to Pu-239. Some of the Pu-239 that is produced is invariably fissioned itself in the course of the continuing reactor operation, and some undergoes successive absorption of further neutrons to become the heavier plutonium isotopes: Pu-240, Pu-241, and Pu-242. These isotopes also fission in the course of continuing reactor operation.

The rate at which plutonium accumulates in a reactor's fuel depends on many factors, including the type and thermal power output of the reactor and the characteristics of its fuel, its coolant, and its moderator (see Box A-2). The quantity and isotopic composition of the accumulated plutonium depend also on how the reactor is operated, particularly on how much fission occurs in fuel until the time it is removed from the reactor, a parameter called the "irradiation" or "burnup" of the fuel (see Box A-3).

High burnup is desirable for electricity production because it means more saleable energy from the fuel, as well as less downtime for refueling (in the case of "batch refuelable" reactor types that need to be shut down in order to remove their spent fuel). But high burnup is undesirable for production of weapon plutonium, both because it leads to greater accumulation of the less desirable even-numbered plutonium isotopes, since much of the desirable Pu-239 product is lost through fission, and because higher burnup means the spent fuel contains larger amounts of radioactive fission products in relation to the quantity of fuel handled, making it more dangerous and difficult to separate out the plutonium.

Plutonium Production Reactors and their Performance

Reactors that countries built specifically to produce plutonium for weapons have nearly all been fueled with natural (unenriched) uranium and moderated by graphite or by heavy water. They have ranged in rated thermal power output from 20 to more than 4,000 megawatts. Many of these reactors were designed to be continuously refuelable, meaning that irradiated fuel can be removed from the reactor core and fresh fuel can be inserted while the chain reaction continues. This feature enables such reactors to operate at the low burnups needed to make weapon-grade plutonium without needing to be shut down frequently to remove and replace the slightly irradiated fuel.

When operated at the very low burnup levels associated with production of weapon-grade plutonium, graphite-moderated and heavy-water-moderated reactors deliver a net rate of plutonium production in the range of 0.9-1.0 gram per megawatt-day of reactor operation. Thus, a very small production reactor with rated thermal capacity of 25 megawatts (the size range of the North Korean graphite-moderated production reactor at Yongbyon) can produce in a year, if it achieves the equivalent of 250 full-power days of operation, about 5.5 kilograms of weapon-grade plutonium. A production reactor l00 times larger, typical of those the United States operated at Hanford and Savannah River, can produce 250 kilograms of plutonium per year.

Reactors designed for electricity production generate plutonium as long as their fuel contains U-238. A typical light-water reactor—a batch-refuelable reactor type—operated at the high burnup optimum for the electric-generating role produces 0.22-0.27 gram of reactor-grade plutonium per megawatt-day. Hence a 3,000 thermal-megawatt light-water reactor operating at full power for 330 days per year will discharge 220-270 kilograms of plutonium per year in its spent fuel.[5]

If such a reactor were operated instead for purposes of optimum production of weapon plutonium at much lower burnup, the net amount of weapon-grade plutonium per year produced in a reactor of given thermal power might be comparable to or somewhat larger than the reactor-grade yield in normal commercial operations but electric power production would be reduced.

Reprocessing Spent Fuel to Extract Plutonium

In order to recover the plutonium produced in a nuclear reactor from the spent fuel it must be chemically separated or reprocessed from the fission products produced, and from the residual U-238. Reprocessing, like uranium enrichment, is a technically demanding and costly operation; because of the intense gamma radioactivity of the fission products, and the health risks posed by the alpha activity of plutonium if inhaled or otherwise taken into the body, reprocessing is much more hazardous than enrichment from the standpoint of health and safety.

Standard practice is to allow the spent fuel to cool for a period of months to years before subjecting it to reprocessing, so that most of the shorter-half-life radionuclides decay away. Even after such cooling, the radiation hazards from spent fuel remain high. The dose rate at the surface of a spent fuel assembly from a modern light-water reactor, at typical commercial burnup and after 10 years of cooling, is around 20,000 rem[6] per hour, and at distance of

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[5] This would correspond to a capacity factor of 330/365 = 0.904 or 90.4 percent (see Box A-3), a level of performance now quite commonly achieved in commercial light-water reactors.

[6] The rem, or "roentgen equivalent man" represents the energy deposited per unit mass of tissue, weighted by the relative effectiveness in inducing health-affecting changes, for each type of radiation. A whole body dose of 500 rem leads to the death of about one half of the individuals exposed.

a meter it is around 2,500 rem per hour. At the far lower burnups associated with production reactors operated to make weapon-grade plutonium, the dose rate is correspondingly lower, but impatience to get the plutonium out may reduce the length of time the fuel is allowed to cool. A fuel assembly from a light-water reactor that had experienced a burnup level appropriate to weapon plutonium production but then cooled for just two years would deliver a dose rate at its surface of nearly 40,000 rem per hour.

The approach to reprocessing that has been used virtually universally for military and civilian purposes alike—called the "PUREX" process—consists of chopping up the radioactive spent fuel into pieces, dissolving these in nitric acid, and then performing a set of solvent extractions on the resulting solution to separate the plutonium, the uranium, and the fission products into three output streams. The uranium or plutonium may emerge finally as nitrates or as oxides. Ultimately, for weapon use, the plutonium would be transformed into metallic form by a simple process.

In all cases, extensive shielding and equipment for remote handling of the materials are required in all stages of reprocessing up to the point where the fission products have been separated from the uranium and plutonium. The equipment must be designed to avoid the possibility that a critical mass of plutonium in a liquid form or as a precipitate could form at any point in the system. And pipes, valves, and vessels must be repairable by remote control, because they will be too radioactive to approach even with protective suits. The technology for this is so demanding and difficult that even major industrial nations have ended up building some reprocessing plants that failed almost immediately and were deemed so expensive to repair that they were abandoned.[7]

Denaturing Plutonium

The best available way to render separated plutonium unusable for nuclear weapons is to unseparate it by remixing it with fission products. Remixing with fission products, to a suitable degree of difficulty for reversing the process, can be achieved by embodying the plutonium in mixed oxide (MOX) reactor fuel and then using that fuel in a power-generating reactor, or by mixing the plutonium with fission products that already exist in storage from prior mili-

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[7] For example, a reprocessing plant built by the General Electric Company in Morris, Illinois, met this fate.

tary or civilian processing of spent nuclear fuel.[8] Both approaches are much costlier and more difficult than the isotopic denaturing of HEU with U-238; moreover the reprocessing technology needed to reseparate the fission products is probably not as demanding as the technology needed to re-enrich uranium.

History of Military Production of NEM

All five of the *de jure* nuclear weapon states used gaseous diffusion and/or gas centrifuge enrichment plants to produce HEU for their weapons. None of these countries is thought to be producing HEU at this time. In the past, these countries produced enriched uranium at a range of enrichment above 20 percent not only for nuclear weapons but also for use in nuclear reactors for propulsion of submarines, other warships, and icebreakers; in research reactors; and in experimental power reactors.

Smaller uranium enrichment plants are operating today in the *de facto* nuclear weapon states India and Pakistan. North Korea is variously reported to have, or to have claimed the right to have, a pilot centrifuge plant, and Iran has announced that it has just started a pilot centrifuge plant and has plans for a future large-scale production plant.

To date, more than 50 reactors have been operated by *de jure*, *de facto*, and aspiring nuclear weapon states to produce military plutonium.[9] The history of these reactors is summarized in Box A-4.

All of the five *de jure* nuclear weapon states have indicated they are not reprocessing plutonium for weapons. A small amount of reprocessing is continuing in Russia because the fuel elements used in three dual-purpose reactors (whose energy output is still needed for regional heating and electric power in Siberia) were not

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[8] These options are discussed in great detail in National Academy of Sciences, Committee on International Security and Arms Control, *Management and Disposition of Excess Weapon Plutonium*, 2 vols. (Washington DC: National Academy Press, 1994 and 1995) and in a large subsequent literature spawned by these reports. See Matthew Bunn, "Plutonium Disposition", in the Controlling Nuclear Warheads and Materials section of the Nuclear Threat Initiative Web site, available as of January 2005, at: http://www.nti.org/cnwm/.

[9] See David Albright, Frans Berkhout, and William Walker, *Plutonium and Highly Enriched Uranium 1996: World Inventories, Capabilities, and Policies* (New York: Stockholm International Peace Research Institute and Oxford University Press, 1997). Albright and colleagues periodically post updates to this work at the Web site of the Institute for Science and International Security available as of January 2005, at: http://www.isis-online.org.

designed for long storage without reprocessing. The plutonium produced is subject to U.S. monitoring to assure it is not diverted to the weapons program. Except for these three Russian reactors, none of the military plutonium production reactors in the *de jure* nuclear weapon states is now operational, although some are mothballed and presumably could be reactivated after some delay. India operates small reprocessing plants at Trombay and Tarapur for its weapon program. A third, at Kalpakkam, does reprocessing for the civilian sector and is sometimes reported to reprocess material for the weapons program. Israel has a reprocessing plant supplied by France in the same underground complex at Dimona that houses Israel's plutonium production reactor. North Korea had a very small reprocessing plant at Yongbyon, which it shut down as part of the Framework Agreement with the United States in 1994, but reportedly claimed to have restarted in early 2003 after that agreement collapsed and North Korea withdrew from the Nuclear Non-Proliferation Treaty (NPT). Technically qualified U.S. visitors found it to be not in operation in early 2004, however.

NEM in the Civilian Sector

As of January 25, 2005, there were 441 power reactors worldwide, totaling 367.25 electrical gigawatts of generating capacity.[10] The annual enrichment requirements for these reactors total about 50 million separative work units (SWU).[11] The low enriched uranium (LEU) being produced under the US-Russian HEU deal by the down blending of 30 tons per year of Russian surplus HEU embodies separative work equivalent to about 11 percent or so of this requirement.[12] The combined capacity of the gaseous diffusion

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[10] See the IAEA Power Reactor Information System (PRIS) Web site, available as of January 2005, at: http://www.iaea.org/programmes/a2/.

[11] The annual enrichment requirement for a 1,000 MWe light-water reactor using 4.4 percent enriched LEU, operating at a burn up of 40,000 thermal megawatt-days per ton of uranium loaded in fuel, and achieving a capacity factor of 85 percent is about 150,000 SWU; this corresponds to about 20,000 SWU per billion kilowatt-hours of nuclear electricity generation. Assuming that this figure will not be far off as an average for all power reactors (given the high proportion of light-water reactors in the mix) and multiplying by the world total nuclear electricity generation of about 2,500 billion kilowatt-hours per year gives 50 million SWU per year.

[12] In 2001, 2002, and 2003 the HEU deal entailed the production of about 900 tons per year of LEU fuel from 30 metric tons per year of HEU. See the USEC status report, available as of January 2005, at: http://www.usec.com/v2001_02/HTML/Megatons_status.asp. Fueling requirements for the world's power reactors are in the range of 8,000 tons of LEU per year.

and gas centrifuge enrichment plants operated by United States, the United Kingdom, France, Russia, China, Japan, Germany, and the Netherlands is about 10 million SWU per year larger than current needs. If the excess capacity were to be used for producing weapon-grade HEU, it would be enough to turn 11,000 tons of natural uranium into 50 tons of 93 percent enriched HEU.[13] These numbers underline the importance and the challenge associated with monitoring to ensure that civilian enrichment capacity is not diverted to production of NEM.

The operation of the world's civilian power reactors leads to the discharge of about 80 tons per year of plutonium embedded in 8,000 tons of spent nuclear fuel. This spent fuel, in which the plutonium is intimately mixed with intensely radioactive fission products and unfissioned U-235 and U-238, goes directly to spent fuel storage pools at the reactor sites. From these, some is later removed for transfer to dry cask storage; and in recent years in about 20 percent of the world's reactors, the spent fuel is removed for transfer to a reprocessing plant where the plutonium is separated for eventual recycling in fresh reactor fuel.

Large reprocessing plants for extracting plutonium from commercial power reactor fuel are in operation at La Hague in France, at Sellafield in England, and at Chelyabinsk in Russia. A much smaller commercial reprocessing plant is operating at Tokai-Mura in Japan. Japan has a larger reprocessing plant near completion at Rokkasho-Mura, but whether it will ever operate is unclear. France has a very small plant for reprocessing breeder reactor fuel at Marcoule. Belgium, the United States, and Germany operated pilot-scale reprocessing plants in the past motivated by commercial possibilities.

In recent years, the rate of production of separated plutonium from reprocessing of spent civilian fuel has been about 20 tons per year, and the rate of fabrication of separated plutonium into mixed oxide fuel for actual loading into power reactors has been about one half that amount. Since the plutonium inventory in spent nuclear fuel has been growing at about 60 tons per year, the total plutonium inventory in spent plus active nuclear fuel has been growing at about 70 tons per year. Moreover, if currently operating commercial reprocessing plants were being utilized to their full

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[13] Producing 1 kilogram of 93 percent enriched HEU requires 226 kilograms of natural uranium input and 200 SWU if the depleted uranium "tails" contain 0.3 percent U-235. Thus 10 million SWU is enough to make 50 tons of 93 percent enriched HEU, starting from 226 × 50 = 11,300 tons of natural uranium.

capacity, the civilian stocks of separated plutonium would be growing at about 30 tons per year.

The greater part of the plutonium embedded in the spent fuel discharged by civil power reactors currently remains in unreprocessed spent fuel in wet or dry storage. Plutonium stored in this form amounted to about 1,250 tons at the end of 2002. Although this material cannot be used in nuclear weapons unless it is first separated in a reprocessing plant, the stocks that exist in this form nonetheless need to be monitored in addition to monitoring reprocessing plants, to ensure that reprocessing of civilian spent fuel for weapon purposes is not occurring in undeclared facilities.

NEM in the civil sector in less developed countries is largely confined to HEU connected with research reactors. The principal exceptions are India, which has reprocessed plutonium from civil power reactors as well as from reactors dedicated to producing military plutonium, and China, which is just beginning the reprocessing of civil plutonium. There are approximately 135 operating research reactors fueled with HEU, in more than 40 countries around the world, ranging from the United States to Ghana.[14] Most of these research reactors have only small amounts of HEU; but some, including a significant number outside the nuclear weapon states, have enough fresh HEU for a bomb. Even more have enough HEU for a bomb if spent HEU that is not radioactive enough to deter suicidal terrorists from taking it and using it in a bomb is taken into account.[15] It should be noted, however, that the fresh fuel itself, although it is categorized as NEM, cannot be used directly to make a nuclear explosive until the uranium is separated from the aluminum or other inert matrix since the small density of the uranium greatly increases the critical mass.

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[14] Matthew Bunn, Anthony Wier, and John P. Holdren, *Controlling Nuclear Warheads and Materials: A Report Card and Action Plan* (Washington, DC: Nuclear Threat Initiative and Project on Managing the Atom, Harvard University, March 2003), and references therein, including especially International Atomic Energy Agency, *Nuclear Research Reactors of the World* (Vienna, Austria: IAEA, September, 2000), available as of January 2005, at: http://www.iaea.org/worldatom/rrdb/ supplemented with personal communications with James Matos, Argonne National Laboratory, and Iain Ritchie, International Atomic Energy Agency, 2002.

[15] See Edwin Lyman and Alan Kuperman, "A Re-Evaluation of Physical Protection Standards for Irradiated HEU Fuel" paper presented at the 24th International Meeting on Reduced Enrichment for Research and Test Reactors (Bariloche, Argentina, November 5, 2002).

BOX A-1

Uranium Enrichment Inputs and Outputs

The magnitude of the task of uranium enrichment can be characterized in three particularly informative ways: the amount of unenriched or low enriched uranium (LEU) input required to obtain the desired, more highly enriched output; the amount of separative work required for the actual sorting of the heavy and light nuclei that enrichment entails; and the amount of electrical energy that a particular separation technology needs in order to perform this work.

The amount of uranium feed required can be calculated from simple balance equations that track the unchanging total quantities of the U-235 and U-238 isotopes. The answer depends on the U-235 concentration in the feed, the U-235 concentration desired in the enriched product, and the concentration specified for U-235 in the depleted uranium waste stream (called "tails"). A materials balance calculation does not depend on which technological process one chooses for doing the enrichment, except to the degree that the final result needs to be adjusted for losses (such as, material ending up coating the insides of pipes), which can vary from one technology to the other.

Natural uranium contains 0.72 percent U-235 and 99.27 percent U-238. (The remainder is 0.006 percent U-234, which can be neglected for our purposes here.) Enrichment levels for typical LEU power reactor fuels are 3-5 percent U-235 fuels, and the weapon-grade HEU preferred by bomb makers is 93 percent U-235. The amount of U-235 left in the tails is a matter of choice, but is usually between 0.2 and 0.4 percent. If natural uranium is cheap and enrichment work is expensive, one chooses a relatively high U-235 concentration in the tails, which increases the natural uranium feed requirement but reduces the separative work. If natural uranium is expensive and enrichment work is cheap, one chooses a lower U-235 concentration in the tails.

If we take the intermediate value of 0.3 percent for the amount of U-235 to be left in the tails, the isotope-balance approach shows that an input of 226 kilograms of natural uranium (containing 0.7 percent U-235) is required to produce an output of 1 kilogram of uranium enriched to weapon grade at 93 percent U-235, neglecting losses in the enrichment plant. A hypothetical gun-type bomb design requiring 60 kilograms of this HEU, for example, would require an input of 13,560 kilograms of natural uranium (60 kg HEU×226 kg natural U per kg HEU = 13,560 kilograms of natural uranium).* (If the uranium comes from ore that contains 0.1 percent uranium, the corresponding ore requirement is 13,560 metric tons.)

To produce an output of 1 kilogram of LEU at the 5 percent U-235 concentration typically used in a modern light-water power reactor, by contrast, requires an input of only 11.5 kilograms of natural uranium. A 1,000 megawatt nuclear reactor of this type will require an input of about 20 tons of fuel of this enrichment per year, so the uranium input to the enrichment plant supporting this reactor must be 20,000 kg LEU×11.5 kg natural U per kg LEU = 230,000 kilograms of natural uranium, or 230 tons, and the corresponding mining requirement is 230,000 ton of ore containing 0.1 percent uranium.

The quantitative measure of how difficult it is to separate isotopes of different atomic masses is the "separative work unit" (SWU). A formula derived from thermodynamics enables calculation of the number of SWU needed to produce a kilogram of uranium enriched to any specified concentration of U-235, given the starting concentration and the concentration desired in the tails.

Application of this formula reveals that producing 1 kilogram of HEU with 93 percent U-235, starting from 226 kilograms of natural uranium and leaving behind 225 kilograms of uranium tails containing 0.3 percent U-235, requires 200 SWU. Thus the enrichment requirement for a hypothetical gun-type weapon containing 60 kilograms of this HEU would be 60 kg HEU×200 SWU per kg of HEU = 12,000 SWU. Producing 1 kilogram of LEU with 5.0 percent U-235 starting from 11.5 kilograms of natural uranium, leaving behind 10.5 kilograms of tails containing 0.3 percent U-235, requires 7.2 SWU. Thus the annual separative work requirement to enrich the uranium fuel for the 1,000 megawatt light-water reactor mentioned above is 20,000 kg of LEU×7.2 SWU per kg of LEU = 144,000 SWU. One sees from this comparison that the amount of enrichment capacity needed to support one large power reactor could, alternatively, perform the enrichment for something like a dozen hypothetical gun-type nuclear weapons per year. Commercially, one SWU costs about $100.

The electric power requirements for uranium enrichment plants range from 100-150 kilowatt-hours per SWU in a centrifuge plants to 2,000-3,000 kilowatt-hours per SWU in gaseous diffusion plants to something like 4,000 kilowatt-hours per SWU for the nozzle/aerodynamic technologies. Laser enrichment technologies are expected to be in the 100-200 kilowatt-hour per SWU range.

The electricity requirement for enriching, by means of gaseous diffusion, the uranium for one hypothetical gun-type bomb using 60 kilograms of 93 percent U-235 HEU would therefore be in the range of 12,000 SWU×2,500 kilowatt-hours per SWU = 30,000,000 kilowatt-hours. At typical U.S. electricity costs of 7 cents per kilowatt-hour, this is $2 million worth of electricity. This electricity requirement likewise means that a gaseous diffusion complex big enough to enrich the uranium for, say, a dozen of these hypothetical gun-type HEU bombs per year would require the full annual output of a 50 megawatt power plant (which is a size adequate to meet the needs of a town of 50,000 people).

Using a gas centrifuge plant at 125 kilowatt-hours per SWU, on the other hand, would entail electricity requirements 20 times smaller, worth about $100,000 per bomb, and needing only 2.5 megawatts of dedicated electricity generating capacity to make a dozen or so hypothetical gun-type HEU bombs per year.

* See Chapter 3, page 114, for the basis for the figure of 60 kilograms used in the calculations in this box.

BOX A-2

Reactor Types and Terminology

Nuclear reactors fall mainly into three categories: (1) power reactors, which are designed and operated to produce electric power; (2) production reactors, whose purpose is to produce particular nuclides for nuclear-explosive, industrial, or medical purposes; and (3) research reactors, which are used for studying nuclear physics and materials science, and for teaching. Sometimes reactors are used in a dual-purpose mode (e.g., generating power and producing nuclear weapon material, or research and medical isotope production), and a few have been designed from the outset for such dual-purpose use.

Nearly all of the reactors that have been built to date for electric power generation, as well as most of those that have been built for producing weapon material, rely primarily on the fissile uranium isotope U-235 to sustain their fission chain reaction; and most of them do so by exploiting the especially high fission probability of U-235 when exposed to slow neutrons (i.e., those whose speeds are not much higher than those of neutrons in thermal equilibrium with their surroundings). Such reactors are called "slow-neutron," or "thermal" reactors.

Relying on slow neutrons, with their high probability of causing a fission in any U-235 nucleus they encounter, allows maintaining a chain reaction in fuel with a lower concentration of U-235 than would be needed if one were trying to sustain the chain reaction with fast neutrons. (A thermal reactor could similarly rely on a low concentration of one of the other fissile nuclides, U-233 or Pu-239, if desired, as these also have high fission probabilities at low neutron energies.)

Use of fuel with a low concentration of its fissile nuclide(s) has a number of advantages over fast-neutron reactors by being able to operate at a lower power density (watts per cubic centimeter in the reactor core), which reduces the engineering challenges and increases the safety margin, and including (in the case of fuel based on U-235) reduced enrichment requirements. Fast-neutron reactors must compensate for the lower fission probability at high neutron energies by increasing the concentration of fissile nuclei and hence the power density with resulting increased U-235 enrichment costs.

Because fission neutrons are "born" with energies much higher than the energy corresponding to the temperature of their surroundings, a thermal reactor must arrange for the neutrons to slow down to near-thermal velocities (where their probability of causing a fission is high) before they are captured in a nonfission reaction or escape from the reactor. This requires the use of a moderator, a substance in the reactor core that is efficient in slowing down neutrons without absorbing very many of them. (Fast-neutron reactors, by contrast, are designed to minimize presence of moderating materials in the core.)

The best moderator materials are very pure graphite (the purity being required because graphite's impurities would absorb too many neutrons) and heavy water (H_2O in which ordinary hydrogen has been replaced by the heavier hydrogen isotope, deuterium). Ordinary water is a decent moderator but not as good as heavy water because the no-neutron isotope of hydrogen that most ordinary water molecules contain is much more likely to absorb a neutron than is deuterium, which already has one.

Graphite and heavy water are such good moderators, in fact, that a suitably designed reactor using one or the other (or both) is able to sustain a chain reaction using natural uranium, despite its very low U-235 concentration of 0.7 percent. The CANDU (standing for Canada Deuterium Uranium) power reactor is an example; its development enabled Canada and other countries that bought them to generate electricity from nuclear energy without building a uranium enrichment plant or having to buy enriched fuel from someone else.

Because of the desirability of minimizing unproductive absorption of neutrons when trying to make as much plutonium as possible, graphite- and/or heavy-water moderated designs have generally been the reactors of choice for producing plutonium for weapons in the countries that have done so. Many of these reactors were designed to be continuously refuelable, which means the reactor does not need to be shut down in order to remove some of its fuel elements for extraction of their plutonium.

As well as being characterized by its moderator (or lack of one), a reactor type is characterized by its coolant. The function of the coolant is to remove the nuclear generated heat from the core so that the solid fuel and structure do not melt. In power reactors, the coolant also serves to carry this energy to adjacent equipment for conversion to electricity. Some graphite-moderated thermal reactors are gas cooled (employing carbon dioxide, helium, or air); others are cooled with heavy water or ordinary water (which is called light water in this context). In some reactor designs, heavy water or light water serves as both moderator and coolant.

About 85 percent of the world's power reactors are so-called light-water reactors, in which ordinary water plays both roles. These require uranium fuel enriched to 3 to 5 percent in U-235 or similar concentrations of U-233 or Pu-239. They cannot use natural uranium. Recycling the plutonium and unfissioned U-235 from their spent fuel could reduce their raw uranium and enrichment requirements by 25 to 30 percent. This does not pay at current prices for uranium enrichment and fuel reprocessing/recycling. The separation of plutonium from spent fuel increases proliferation risks but a few countries are doing it anyway.

Fast-neutron reactors (usually but somewhat confusingly called just “fast reactors”) cannot be cooled with water because its moderator properties would result in too much slowing down of the neutrons. The attractions of fast reactors are the compactness of their fission cores (which is valuable in some applications but not generally in electricity generation), the energy and intensity of the neutron fluxes they generate (a useful property for certain research and industrial applications), and the high rate at which they can produce plutonium from U-238.

The possibility of producing more plutonium than does a thermal-neutron reactor arises because fissions induced by fast neutrons release, on the average, more neutrons per fission than fissions induced by slow neutrons, and these extra neutrons are potentially available for plutonium-producing absorption by U-238. Gas and liquid metals are the main possibilities for cooling fast reactors. Liquid metals have been the predominant choice so far, because of their greater capability for heat removal.

The sodium-cooled liquid metal fast breeder reactor (LMFBR) is the fast-reactor type that has attracted the most interest, including prototype and pilot plant development in a number of countries. But it has proven, however, to be a very demanding technology whose principal potential advantage—the capacity to conserve uranium by breeding U-238 into Pu-239 at rate sufficient to refuel itself with some left over—has not paid off in a world where uranium continues to be very cheap and reprocessing fuel to recover bred plutonium for recycling continues to be very expensive.

If it is desired to minimize rather than to maximize the production of plutonium—as might be sought in circumstances where the potential for diversion of the plutonium for use in weapons is of particular concern—it is necessary to avoid having very much U-238 in the reactor. One reactor design that can achieve this is the high-temperature gas-cooled reactor (HTGR), a thermal reactor that can operate using a combination of U-235 and U-233 as its fissile material. The remaining heavy nuclides present in the fuel are a mixture of thorium-232 and a modest amount of U-238. U-233 is produced in this fuel cycle as a result of the absorption of fission neutrons in the Th-232.

BOX A-3

Reactor Size and Performance

Reactors can be of different sizes and types. Size is an important characteristic in determining the potential production of nuclear-explosive materials of which a given reactor is capable. The most relevant measure of size is the "rated thermal capacity," which is the rate of release of nuclear energy in the reactor core for which the reactor has been designed and at which it is authorized to operate.

The usual units for rated capacity are megawatts of thermal energy flow. An energy flow of a megawatt sustained over a day adds up to 1 million joules per second multiplied by the 86,400 seconds in a day, or 86.4 billion joules. This unit of energy is called a megawatt-day. The fission of one gram of uranium or plutonium leads to the deposition in the reactor of about 82 billion joules of fission energy, which corresponds to about 0.95 of a megawatt-day. Rounding this off to one megawatt-day of thermal energy release per gram of heavy nuclei fissioned gives a rule of thumb that is often used for making estimates of nuclear fuel consumption rates in reactors, based on their rated capacity and the fraction of the time that they achieve it.

The theoretical maximum amount of thermal energy that a reactor can generate in a year is given by its rated capacity in megawatts multiplied by the number of days in a year, hence 365 megawatt-days of energy per year per megawatt of rated capacity. The actual output of energy that a reactor achieves in a year, divided by this theoretical maximum that it would have generated if it had operated at 100 percent of its rated capacity for 100 percent of the time, is called its "capacity factor" for the year.

This measure of fission energy extracted from fuel is called the "irradiation" or burnup; its units are megawatt-days per kilogram of heavy metal (uranium or plutonium) loaded into the reactor (MWd/kgHM). The burnup in today's large commercial electric power reactors is typically between 30 and 50 MWd/kgHM, but in reactors being operated to produce plutonium for weapons, the figure has been much lower, on the order of 1.0 MWd/kgHM.

Large light-water reactors built for electricity generation have rated thermal capacities in the range of 3,000 megawatts (at 33 percent electrical generation efficiency, corresponding to about 1,000 megawatts of electrical capacity). The smallest plutonium production reactors likely to be of interest would be around 20 megawatts.

Using the rule of thumb of one gram of heavy nuclei fissioned per megawatt-day of thermal output indicates that a large power or production reactor rated at 3,000 thermal megawatts will fission about 3 kilograms of heavy nuclei per full-power day of operation. (Since the mass of the radioactive fission products is very nearly the same as the mass of the nuclei whose fission produced them, such a reactor generates about 3 kilograms per full-power day of radioactive fission products.) At the other end of the size range, a production reactor rated at 20 thermal megawatts will fission about 20 grams of heavy nuclei per day of full-power operation, yielding 20 grams of fission products and about 20 grams of Pu-239.

BOX A-4

History of Plutonium Production Reactors

United States: 9 graphite-moderated, light-water-cooled production reactors deployed at the Hanford site and 5 heavy-water-moderated production reactors deployed at Savannah River (none still operating).

Former Soviet Union/Russia: 13 graphite-moderated, light-water-cooled production reactors at Chelyabinsk, Tomsk, Krasnoyarsk (of which 3 dual-purpose reactors are still operating to supply heat and electricity in the Krasnoyarsk and Tomsk regions).

United Kingdom: a total of 10 graphite-moderated, gas-cooled production reactors at Windscale, Calder Hall, and Chapel Cross (none still operating).

France: 9 graphite-moderated, gas-cooled reactors at Marcoule and two heavy-water moderated reactors at Celestin (none still operating); the prototype liquid-metal-cooled, fast-neutron breeder reactor (the Phénix) was shut down for maintenance between 1998 and 2003 and has reportedly returned to operation.

China: 2 graphite-moderated, light-water-cooled reactors, one at Jiuquan and one at Guangyuan (none still operating).

Israel: a heavy-water-moderated, air- and heavy-water-cooled production reactor at Dimona.

India: 2 heavy-water-moderated production reactors near Bombay.

North Korea: a graphite-moderated, gas-cooled production reactor at Yonbyon.

Appendix B

Acronyms

ABM	Anti-ballistic missile
CTBT	Comprehensive Nuclear Test Ban Treaty
CSA	Canned subassembly
CTR	Cooperative threat reduction
FMCT	Fissile Material Cutoff Treaty
G8	Group of 8
GTRI	Global Threat Reduction Initiative
HEU	Highly enriched uranium
HTGR	High-temperature gas-cooled reactor
ICBM	Intercontinental ballistic missile
IAEA	International Atomic Energy Agency
INF	Intermediate range nuclear forces
JCIC	Joint Compliance and Inspection Commission, START I
LEU	Low enriched uranium
LWR	Light-water reactor
MOX	Mixed oxide of plutonium and uranium
MPC&A	Material protection, control, and accounting
NEM	Nuclear-explosive materials
NPT	Nuclear Non-Proliferation Treaty
NTM	National Technical Means
PSI	Proliferation Security Initiative

SALT	Strategic Arms Limitation Treaty
SWU	Separative work unit
SHA	Secure hash algorithm
SLBM	Submarine-launched ballistic missile
START	Strategic Arms Reduction Treaty
WMD	Weapons of mass destruction

Appendix C

Biographical Sketches of Committee Members

2000 to 2004

John P. Holdren (NAS, NAE), Chair, is Teresa and John Heinz Professor of Environmental Policy and Director of the Program in Science, Technology and Public Policy, John F. Kennedy School of Government, and Professor of Environmental Science and Public Policy in the Department of Earth and Planetary Sciences at Harvard University. He was a member of President Clinton's Committee of Advisors on Science and Technology.

John D. Steinbruner, Vice Chair for Studies, is Director of the Center for International and Security Studies at the University of Maryland and former Director of the Foreign Policy Studies Program of the Brookings Institution. He has held faculty positions at Yale, Harvard, and MIT and was a member of the Defense Policy Board.

Catherine McArdle Kelleher, Vice Chair for Dialogues, is a Senior Research Professor at the U.S. Naval War College and former editor of the Naval War College Review. She also served as Director of the Aspen Institute Berlin, U.S. Deputy Assistant of Defense for Russia, Ukraine, and Eurasia, and Personal Representative of the Secretary of Defense in Europe.

William F. Burns, Major General (USA, retired), Study Co-Chair, is former Director of the U.S. Arms Control and Disarmament Agency and former Commandant of the U.S. Army War College. He served as ambassador to the Safe, Secure Dismantlement (SSD) negotiations regarding the denuclearization of the former Soviet Union.

George Lee Butler, General (USAF, retired) is former Commander-in-Chief of the Strategic Command, where he actively promoted new assessments of U.S. nuclear policy and programs to adjust to the post-Cold War era. He also served as Director of Operations, HQ and as Director for Strategic Plans and Policy. He was recently Director/President of the Second Chance Foundation.

Christopher Chyba is Co-Director of Stanford's Center for International Security and Cooperation, and Associate Professor in the Department of Geological and Environmental Sciences. He served on the national security staff of the White House from 1993 to 1995.

Stephen P. Cohen is a Senior Fellow in the Foreign Policy Studies program of the Brookings Institution. Prior to joining Brookings, he was a Professor of History and Political Science at the University of Illinois at Urbana-Champaign and Director of its Program in Arms Control, Disarmament, and International Security.

Susan Eisenhower is President of the Eisenhower Institute. Formerly Chairman and co-founder of the Center for Political and Strategic Studies (CPSS), she joined the Institute as CEO when the two organizations combined programs.

Steve Fetter, Study Co-Chair, is a Professor in the School of Public Affairs at the University of Maryland. A physicist, he was a special assistant to the Assistant Secretary of Defense for International Security Policy, and a Council on Foreign Relations fellow at the State Department.

Alexander H. Flax (NAE) is President Emeritus of the Institute for Defense Analyses and former Home Secretary of the National Academy of Engineering. From 1964-69 he was Assistant Secretary for Research and Development of the Department of the Air Force.

Richard L. Garwin (NAS, NAE, IOM) is IBM Fellow Emeritus of the Thomas J. Watson Research Center of the IBM Corporation. He served the President's Science Advisory Committee as both a consultant and a member and was chair of the State Department’s Arms Control and Nonproliferation Advisory Board and its predecessors from 1992 to 2001.

Rose Gottemoeller is a Senior Associate at the Carnegie Endowment for International Peace, specializing in arms control, nonproliferation and nuclear security issues. From 1998 to 2000, she served in the Department of Energy as Assistant Secretary for

Nonproliferation and National Security and then as Deputy Undersecretary for Defense Nuclear Nonproliferation. From 1993 to 1994 she was Director for Russia, Ukraine, and Eurasia Affairs on the National Security Council in the White House.

Margaret A. Hamburg (IOM) is Senior Scientist, Nuclear Threat Initiative, Washington, D.C. Before taking on her current position, she was the Assistant Secretary for Planning and Evaluation, U.S. Department of Health and Human Services. Prior to this, she served as the Commissioner of Health for the City of New York.

Raymond Jeanloz (NAS) is Professor in Earth and Planetary Science at the University of California at Berkeley. His expertise is in the properties of materials at high pressures of temperatures and in the nature of planetary interiors.

Spurgeon M. Keeny, Jr., Study Editor-in-Chief is a Senior Fellow at the National Academy of Sciences. He has held a number of high-ranking positions within the U.S. government. These included: Director of the office responsible for U.S. Air Force intelligence estimates on the Soviet nuclear weapons program (1948-1954); Technical Assistant to the President's Science Advisor (1958-1969); senior member of the National Security Council staff responsible for arms control and nuclear programs and policy (1963-1969); and Deputy Director of the U.S. Arms Control and Disarmament Agency (1969-1973). From 1985 to 2001 he was President and Executive Director of the Arms Control Association.

Charles Larson, Admiral (USN, retired) was a nuclear submarine commander and commander of submarine forces, served two tours as Superintendent of the U.S. Naval Academy (1983–1986; 1994–1998), was commander of the U.S. Pacific Fleet (1990–91), and Commander in Chief of the unified U.S. Pacific Command (1991–94). He was involved in arms control and nuclear weapons policy issues as a Flag Officer (Admiral). He was recently a Senior Fellow at the Center for Naval Analyses.

Joshua Lederberg (NAS, IOM) is Sackler Foundation Scholar, President Emeritus at The Rockefeller University in New York, and a Consulting Professor of the Institute for International Studies at Stanford University. Dr. Lederberg was awarded the Nobel Prize in Physiology or Medicine in 1958 for his pioneering work in the field of bacterial genetics with the discovery of genetic recombination in bacteria.

Matthew Meselson (NAS, IOM) is Thomas Dudley Cabot Professor of the Natural Sciences at the Department of Molecular and Cellular Biology at Harvard University, and Co-Director of the Harvard Sussex Program on CBW Armament and Arms Limitation. He was a member of the State Department's Arms Control and Nonproliferation Advisory Board.

Albert Narath (NAE) is the former President of the Sandia Corporation and Director of the Sandia National Laboratories. He is also the former President and Chief Operating Officer, Energy and Environment Sector, Lockheed Martin Corporation. He has held leadership positions on a number of advisory boards and committees for the U.S. Department of Energy and other federal agencies.

Wolfgang K.H. Panofsky (NAS), Chair Emeritus of CISAC, is Professor and Director Emeritus at the Stanford Linear Accelerator Center at Stanford University. His field is experimental high energy physics. He was a member of the President's Science Advisory Committee under Presidents Eisenhower and Kennedy and a member of the General Advisory Committee on Arms Control to the President under President Carter.

C. Kumar N. Patel (NAS, NAE) is Chairman of Pranalytica, Inc. and a Professor of Physics and former Vice Chancellor for Research of the University of California at Los Angeles. He is a former Executive Director of the Research, Material Science, Engineering, and Academic Affairs Division of AT&T Bell Laboratories.

Jonathan D. Pollack is Professor of Asian and Pacific Studies and former Chairman of the Strategic Research Department at the U.S. Naval War College, where he also directs the College's Asia-Pacific Studies Group. Prior to assuming his current responsibilities, he served as Senior Advisor for International Policy at the RAND Corporation.