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Verifying Nuclear Disarmament

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Pragmatic steps toward ideal objectives

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Preface

In recent years the level of international debate on the elimination of nuclear weapons has increased significantly. During negotiations for the comprehensive test ban treaty (CTBT), many countries called for further and faster progress toward nuclear disarmament. The Canberra Commission on the Elimination of Nuclear Weapons, a group of high level experts from over a dozen countries, called on the nuclear weapon states to commit to the elimination of all nuclear weapons and proposed practical steps leading toward elimination.[1] In recommending elimination, the Commission joins a growing number of respected former military commanders, statesmen, and defense analysts who advocate serious consideration of nuclear disarmament as a long-term policy objective.[2]

Yet, while support for elimination is growing, skepticism regarding the feasibility of that goal remains high. Critics of nuclear disarmament argue that, regardless of whether it is *desirable*, elimination will never be *feasible* because it will be impossible to verify satisfactorily that no country has hidden a secret cache of nuclear weapons or is trying clandestinely to produce a small arsenal. Even proponents of elimination recognize that an adequate verification system is essential if states are to agree at some point in the future to take the final step to ban nuclear weapons.

Given the difficulty of detecting a few hidden nuclear devices or a small supply of fissile materials, no verification regime can be expected to confirm that all states are in absolute compliance with an agreement to eliminate nuclear weapons. It should be possible, however, to devise a verification regime that can reduce significantly the level of uncertainty to a point where states are willing to accept the residual risk in order to gain the anticipated benefits associated with elimination. As the Canberra Commission points out, ultimately, states will have to make "a political judgement . . . on whether the levels of assurance possible from the verification regime are sufficient"—a judgement that likewise has been required for all arms control and disarmament agreements currently in place.[3]

What would such a verification regime entail? What standard of verification could be achieved? How great would the residual risks be, and would states be willing to accept these risks?

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[1] The Canberra Commission was convened as an independent commission by the then Australian Government in November 1995. The Canberra Commission on the Elimination of Nuclear Weapons, *Report of the Canberra Commission on the Elimination of Nuclear Weapons* (Canberra, Australia: Department of Foreign Affairs and Trade, August 1996).

[2] Such recommendations can be found in: *An Evolving US Nuclear Posture: Second Report of the Steering Committee, Project on Eliminating Weapons of Mass Destruction* (Washington, DC: The Henry L. Stimson Center, December 1995); General Andrew J. Goodpaster, *Further Reins on Nuclear Arms: Next Steps for the Major Nuclear Powers,* Consultation Paper (Washington, DC: The Atlantic Council, August 1993); Joseph Rotblat, Jack Steinburger, and Bhalchandra Udgaonkar, *A Nuclear-Weapon-Free World: Desirable? Feasible?* (Boulder, Colo.: Westview, 1993); and Regina C. Karp, *Security without Nuclear Weapons? Different Perspectives on Non-Nuclear Security* (Oxford: Oxford University Press, 1992).

[3] The Canberra Commission, *Report*.

In his paper on "Verifying Nuclear Disarmament," Dr. Steve Fetter observes that it is impossible to predict accurately "the political and technical circumstances" under which the nuclear-weapon states would consider seriously the elimination of nuclear weapons or the standard of verification that states would consider adequate under such circumstances. He therefore adopts a "bottom-up" approach to the problem of verification. He begins by examining the range of possible techniques both to verify the complete dismantlement of nuclear arsenals and to provide the international community timely warning of attempts to build nuclear weapons, in order to determine what standard of verification could be achieved. He then explores the political circumstances under which this standard would be seen as "adequate."

Many of the verification techniques Fetter examines "do not depend on dramatic improvements in world politics" and rely on technology that is now available or under development. The foundations for a verification regime for nuclear disarmament already exist in current arms control agreements, such as the INF, START, and NPT treaties. Current verification arrangements could be expanded, Fetter suggests, to increase the possibility of detecting clandestine attempts to build nuclear arsenals and to monitor limitations on all delivery vehicles. Additional measures, such as tagging nuclear warheads, monitoring dismantlement through perimeter-portal systems, and establishing international controls on fissile materials, would enhance confidence in the regime. The financial costs of verifying disarmament will not be small, Fetter warns, but neither will they be extreme in comparison with other arms control agreements.

Efforts to expand verification should begin now, Fetter advises. Early steps to declare inventories and facilities related to nuclear weapons—including numbers and types of warheads, delivery vehicles, fissile materials stocks, and production facilities and histories—and steps to verify the accuracy and completeness of these declarations are critical. As Fetter warns, "Unless the nuclear-weapon states begin this process today, when stockpiles are huge and shrouded in secrecy, they will fail to lay the necessary foundation for nuclear disarmament, because today's uncertainties will be magnified greatly as we move from tens of thousands to hundreds of warheads and ultimately to zero." Early declarations would enhance transparency and act as an important confidence-building measure, paving the way for further reductions.

While developing effective technical tools for verification is a vital step on the path to elimination, in the end, political conditions will determine whether states will consider verification techniques adequate for a nuclear weapons ban to be adopted. Verification must be viewed in its political context and coupled with other mechanisms to reduce incentives to cheat. Fetter concludes that "nuclear disarmament will be possible not when small-scale cheating or break-out is impossible, but rather when nations become convinced that such cheating no longer seems very likely or very important." Yet, the elimination process is likely to be iterative. Developing and implementing effective verification techniques as a matter of priority will build mutual confidence and help to create the necessary political conditions for further progress toward elimination.

This study of verification tools for disarmament is the second in a series that examines key challenges for the elimination of weapons of mass destruction. Other studies in this series will explore the implications of further reductions of nuclear weapons for US defense policy; the challenges of safeguarding against violations of a ban on nuclear weapons; and the linkages between biological, chemical, and nuclear weapons; and the relationship between deeper cuts in offensive weapons and the development of defensive systems. These studies seek to identify the main obstacles to the progressive elimination of mass destruction weapons from all nations and to propose solutions—both intermediate measures and longer-term approaches—to overcome these obstacles.

This series is part of the Henry L. Stimson Center's Project on Eliminating Weapons of Mass Destruction, which seeks to encourage a national and international debate on the long-term nuclear future. The project is based on the premise that the end of the Cold War, dissolution of the Soviet Union, and grave dangers of proliferation provide both reason and opportunity to reexamine fundamental assumptions regarding the relative benefits and risks associated with weapons of mass destruction. Through research and public education efforts, the Center seeks to explore the obstacles to, and implications of, the progressive elimination of all nuclear, chemical, and biological weapons from all states, and to consider measures that might bring all states closer toward that goal.

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About the Author

Steve Fetter is an associate professor in the School of Public Affairs at the University of Maryland, where he teaches and writes about the technical aspects of security and environmental policy. During the 1996–97 academic year, he is a visiting fellow at Stanford’s Center for International Security and Arms Control. Professor Fetter is a consultant to several US government agencies, a member of the National Academy of Sciences’ Committee on International Security and Arms Control, and a fellow of the American Physical Society. Previously he has been special assistant to the Assistant Secretary of Defense for International Security Policy; Council on Foreign Relations fellow at the State Department; postdoctoral fellow at Harvard University’s Center for Science and International Affairs; visiting scientist at MIT’s Plasma Fusion Center; and the first arms-control fellow at Lawrence Livermore National Laboratory. He received a Ph.D. in energy and resources from the University of California, Berkeley, and a S.B. in physics from MIT. Fetter’s articles on policy-related issues have appeared in *Science, Nature, Scientific American, International Security, Science and Global Security, Bulletin of the Atomic Scientists,* and *Arms Control Today*. He has contributed chapters to a dozen edited volumes on arms control, and is author of the book *Toward a Comprehensive Test Ban*.

List of Abbreviations

ALCM	Air-launched cruise missile
CTBT	Comprehensive Test Ban Treaty
CWC	Chemical Weapons Convention
HEU	Highly enriched uranium
IAEA	International Atomic Energy Agency
ICBM	Intercontinental ballistic missile
INF Treaty	Intermediate Nuclear Forces Treaty
LEU	Low-enriched uranium
NPT	Nuclear Non-Proliferation Treaty
OECD	Organisation for Economic Co-operation and Development
PNE	Peaceful nuclear explosion
SLBM	Submarine-launched ballistic missile
SLCM	Sea-launched cruise missile
SLV	Space launch vehicle
START	Strategic Arms Reduction Treaties

Verifying Nuclear Disarmament

Many essays on nuclear strategy and arms control include a discussion of the possible elimination of nuclear weapons. Commentators differ on whether nuclear disarmament would be desirable, but many argue that disarmament is impractical because it could not be verified. Three reasons are often offered for such pessimism. First, nuclear weapons are small and difficult to detect, and one could not be sure that a few weapons had not been hidden away. Second, nuclear weapons are so destructive that a mere handful would confer enormous military and political advantages over non-nuclear adversaries. Finally, nuclear know-how cannot be eliminated, and any nation that had dismantled its nuclear weapons would be capable of quickly assembling a new arsenal from scratch or using civilian nuclear materials. Because of the difficulty of verifying that other states had eliminated all their weapons and providing adequate warning of their rearming, it is argued, states would not agree to disarm in the first place.

While a degree of skepticism is healthy, it is not so obvious that nuclear disarmament could not be adequately verified, particularly in the sort of world in which disarmament would be considered a serious option. The international community, for example, recently concluded that South Africa, which had built a half-dozen nuclear bombs, has disarmed completely and has placed all of its nuclear materials under international safeguards. Similarly, international inspectors are now confident that they have uncovered all significant nuclear-weapon facilities and activities in Iraq, despite attempts by Iraq to hide such facilities and activities. Moreover, the International Atomic Energy Agency (IAEA) and national intelligence agencies are developing new techniques to find clandestine production facilities and to verify declarations of nuclear material production.

This paper examines the techniques that could be used to verify that nuclear arsenals had been dismantled and to provide timely warning of any attempt to build nuclear weapons. Although no verification regime could provide absolute assurance that former nuclear-weapon states had not hidden a small number of nuclear weapons or enough nuclear material to build a small stockpile, verification could be good enough to reduce remaining uncertainties to a level that might be tolerable in a more transparent and trusting international environment. And although the possibility of rapid break-out will be ever present in modern industrial society, verification could provide the steady reassurance that would be necessary to dissipate residual fears of cheating. Verification will never be so effective that it can substitute for good relations between nations, but it can play an essential role in consolidating the trust that is necessary to support the ongoing process of reducing nuclear arsenals, perhaps all the way down to zero.

Defining Disarmament

Before diving into a discussion of how nuclear disarmament might be verified, it is wise to ask exactly what "disarmament" might mean and what would constitute adequate verification that disarmament had been achieved and was being maintained. At a minimum, disarmament would require the dismantling of all nuclear explosive devices under national control.[1] How confident must we be that all such devices had been dismantled? What barriers should be erected to delay an attempt to build nuclear weapons? How confident must we be in detecting an attempt to rebuild a nuclear arsenal of a given size? How much warning must we have of such an attempt?

Unfortunately, it is impossible to answer these questions in general terms. What we mean by disarmament, the constraints we would impose on rearmament, the demands that we would place on the verification regime, and the resources and authority we would be willing to assign the task, would depend first and foremost on the general shape of the world order in which disarmament is considered. Nuclear disarmament could be pursued under conditions of unprecedented world peace and tranquillity, or under widespread and intense fear of nuclear weapons triggered by chaos in Russia, accidental or unauthorized use of nuclear weapons, war in Korea, the Middle East, or South Asia, or blackmail by rogue states or terrorist groups that somehow obtain nuclear weapons. Our standards for disarmament and verification are likely to be considerably lower if disarmament is motivated by a general recognition of the irrelevance of nuclear weapons to maintaining peace and security, rather than a belief that their continued existence is maleficent and destabilizing.

The standard of verification also will depend on the set of safeguards that are erected in connection with the disarmament agreement to protect against the possibility of violations. Safeguards might include defenses against nuclear weapons delivered by aircraft, missiles, or covert means; security guarantees that pledge states to aid victims of nuclear attack or to punish nuclear aggressors; international nuclear or conventional forces of sufficient strength to deter or punish the use of nuclear weapons; or preparations to quickly rebuild national nuclear forces should the verification regime detect violations. Some analysts promote the deterrent effect of nations being ready to "go nuclear" in response to a violation of the disarmament agreement; in this view, disarmament might mean not having assembled weapons, but maintaining the capacity to assemble them in a matter of weeks.[2] Others recommend a ban on nuclear activities of all kinds—civilian as well as military—to build the biggest possible firebreak to rearmament.[3]

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[1] I leave open the possibility that nuclear disarmament could include a situation in which some number of nuclear weapons remain under international control. This would raise a number of questions with important implications for verification: Who would maintain such weapons? On whose territory would they be based? Would command and control arrangements be so robust as to make seizure by a national government difficult or impossible? For an exploration of this topic, see Roger D. Speed, "The International Control of Nuclear Weapons" (Stanford: Center for International Security and Arms Control, June 1994).

[2] See Jonathan Schell, *The Abolition* (New York: Avon, 1984); also Michael J. Mazarr, "Virtual Nuclear Arsenals," *Survival* 37, no. 3 (Autumn 1995): 7–26.

[3] Theodore B. Taylor, "A Ban on Nuclear Technologies," *Technology Review* 98, no. 6 (August/September 1995): 76.

There are strong interactions between verification and safeguards. Some safeguards make verification more difficult: if nations are permitted to maintain a capacity to manufacture nuclear weapons, this obviously would make it more difficult to verify that all weapons had been eliminated, and it would complicate efforts to detect and provide timely warning of violations. Other safeguards, such as strong defenses or security guarantees, could permit a lower standard of verification. Verification and safeguards also can be synergistic: the more certain and extensive the warning provided by the verification regime, the more effective is the threat to respond to a violation with coordinated diplomatic, economic, or military action.

Thus, it is possible to imagine situations in which the standard of verification might be relatively low and readily achievable. If, for example, technical breakthroughs made possible extremely robust defenses against small nuclear attacks, then small, clandestine nuclear forces might not have sufficient political or military value to justify the risk of violating the disarmament agreement, and fear of such attacks might not threaten the stability of a disarmament agreement. Similarly, if collective security arrangements were strong, as measured by the political will and the military ability to punish violators, or if states believed that any advantage that could be obtained by violating the agreement would be short-lived (e.g., because other states would rebuild quickly their arsenals), then incentives to defect from the regime would be small.

We should, of course, bear in mind that none of these conditions exist today. It is thus easier to imagine situations in which disarmament would be difficult to verify: the existence of technically capable aggressive states; the lack of a cooperative security regime that incorporates all the great powers; or technical breakthroughs that make uranium enrichment possible on a small scale.

Disarmament will not happen soon. The political and technical circumstances in which nuclear disarmament would be considered seriously by the nuclear-weapon states cannot be predicted with any accuracy. We cannot say whether one weapon or one hundred illegal weapons would be a “significant” violation, or whether one day or one year would represent “timely” warning of such a violation. What we can do is investigate the range of possible verification techniques, intelligence capabilities, and inspection privileges and infer from this what sort of verification standard might be achievable. Having determined what standard of verification is *possible*, we can then discuss the sort of international political environment and types of safeguards that would be necessary to make this standard of verification *adequate* for disarmament.

Having said that, we should not fall into the trap of considering verification provisions that are too visionary, fanciful, or Draconian. For example, the elimination of the nuclear-power industry generally would be considered an unreasonable condition for a nuclear-weapon-free world, no matter how it might simplify verification.[4] We could and should consider, however, significant restrictions

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[4] Some people (particularly those who oppose nuclear power for other reasons) might believe that eliminating the nuclear-power industry would be a small price to pay for the abolition of nuclear weapons. And if this was a *necessary* condition—that is, if the elimination of nuclear power was generally regarded as necessary to achieve disarmament—then such a bargain might be struck. There is, however, little chance that experts and policymakers would arrive at such a

on the nuclear-power industry that would facilitate verification. Nor should we discuss verification provisions that rely on the establishment of supranational authority beyond what is provided for under the United Nations Charter. Not only is such an evolution in the international system entirely speculative, but by making such an assumption, verification problems could be dismissed simply by conjuring up an international authority with intelligence services and police forces sufficient to detect and deal with any threat to the regime. We must deal with the verification issue in a realistic context.

Dismantling Nuclear Arsenals

The central goal of a disarmament agreement would be to eliminate the threat of nuclear attack by eliminating the entire spectrum of weapon systems, materials, equipment, and facilities that had been used to create and maintain this threat. The first job of the verification regime would be to certify, with a reasonably high level of confidence, that the nuclear arsenals of all nations had been dismantled completely. For verification purposes, nuclear arsenals can be considered to have three main types of components: delivery vehicles and their launchers, nuclear warheads, and fissile materials.[5] Each of these components has an associated complex of production and support facilities that also must come under control. In each case, the goal of verification is to ensure that these items, materials, and facilities have been dismantled, destroyed, or converted to peaceful or non-nuclear military uses under appropriate international monitoring.

The dismantling of nuclear arsenals most likely would proceed in a series of discrete phases over a period of several decades. The Strategic Arms Reduction Treaties (START), in which the United States and Russia commit to reduce the number of deployed strategic warheads on each side from over 10,000 to 6,000 and then to 3,500 warheads by 2003, is the first step in this process. Subsequent agreements might reduce US and Russian forces still further, down to perhaps 1000 to 2000 warheads on each side, including non-strategic and non-deployed warheads. The United Kingdom, France, and China might join the process at this point, with each nuclear-weapon state reducing its arsenal to a few hundred warheads or less. Only after confidence in these reductions had been established firmly is it likely that a decision by all the declared and de-facto weapon states to ban nuclear weapons would be possible. The details of these phases are not very important here, however, because over most of this period the disarmament process would be indistinguishable from a deep reduction to some small but finite number of nuclear weapons, as would be the means of verification.

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conclusion; they likely would conclude that rigorous safeguards would allow nuclear power to survive in a nuclear-weapon-free world. Nuclear power is simply too important to the energy future of the world to be given up without convincing proof that disarmament is impossible without it. Even if such proof was in hand, it would be no small matter to convince policymakers that the benefits of disarmament outweighed those of nuclear power.

[5] We omit from this analysis the command, control, communications, surveillance, and intelligence systems that play vital roles in nuclear targeting, monitoring the status and assessing the capabilities of opposing nuclear arsenals, and controlling the launch of nuclear forces.

For both reductions and disarmament, the verification process would begin with a declaration by each state possessing nuclear weapons of the location and characteristics of the weapons and related facilities, followed by a series of inspections to verify the accuracy of the declaration. The declaration would establish a baseline from which reductions could proceed. The declaration also would increase our understanding of the nature and operation of each state's nuclear-weapon complex, improving our ability to monitor and verify the disarmament process. It might be desirable during the course of the baseline inspections to subject some of these facilities to continuous monitoring to ensure that nothing is added or removed without appropriate reporting.

Once an agreed inventory of nuclear weapons and related facilities and materials was established, each item would be dismantled or converted to peaceful use according to specified procedures under international monitoring. The declaration would be updated periodically to reflect these changes. In some cases, continuing inspections would be necessary to verify that certain facilities had not been recommissioned or diverted to military use. During the reduction process, and for a very long time thereafter, surprise inspections would be conducted to search for evidence of hidden weapons or facilities that might have been omitted from the declaration.

The following sections describe how the process of declarations and inspections would be applied to delivery vehicles, warheads, and fissile materials. This is followed by an analysis of the only example of voluntary and verified nuclear disarmament—the case of South Africa. I then draw general conclusions about the degree of confidence that states would be likely to have that nuclear arsenals had been eliminated completely.

Delivery Vehicles

To date, nuclear arms control has focused almost exclusively on restricting the number and operational characteristics of delivery vehicles—particularly ballistic missiles and long-range aircraft. The reasons for this are simple. First, delivery vehicles and their launchers are relatively easy to count; silos, submarines, and bombers, unlike warheads, cannot be hidden easily from spy satellites. Second, delivery vehicles are expensive, typically costing up to ten times more to produce and maintain than the nuclear warheads they are designed to carry.[6] Third, nuclear warheads that are mounted on long-range delivery vehicles are considered to have far more military significance than warheads in storage or on short-range delivery systems. Delivery vehicles thus have been the chief currency of nuclear capability, and their elimination would be a natural focus of disarmament efforts.

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[6] In the United States, the design, testing, and production of the nuclear warhead accounted for 10 to 15 percent of the complete cost of a nuclear weapon system. (Paul S. Brown, "Nuclear Weapon R&D and the Role of Nuclear Testing," *Energy and Technology Review*, September 1986, 7.) The United States spent a total of $2,000 billion on research, development, testing, production, and deployment of delivery vehicles, compared to $380 billion spent on nuclear warhead research, development, testing, and production overall. (Kevin O'Neill, "Nuclear Materials Production, and Nuclear Weapons Research, Development, Testing, and Manufacture, 1940–1995," Nuclear Weapons Cost Study Project, The Brookings Institution [to be published].).

Recent US–Russian arms control agreements provide a useful model for verifying the elimination of nuclear delivery vehicles on a multilateral basis. The Intermediate Nuclear Forces (INF) and START treaties are particularly instructive in three respects. First, these treaties established comprehensive and ongoing exchanges of data on the number, location, and technical characteristics of all long-range US and Soviet (now Russian) nuclear delivery vehicles, as well as facilities for their production, testing, storage, maintenance, repair, and training. The accuracy of this data is confirmed by initial and continuing inspections of the declared facilities. Second, these treaties established procedures by which delivery vehicles and launchers can be verifiably eliminated or converted to a non-nuclear mission, and for ending nuclear-weapon-related activities at production and support facilities. The elimination or conversion is verified by a combination of national technical means and on-site inspections, depending on the type of delivery vehicle or facility. Third, the treaties provided for "suspect-site" inspections to verify that equipment or activity limited by the treaty is not present at other, undeclared facilities.

In most respects, the INF and START treaties provide a complete set of tools to verify the elimination or conversion of nuclear delivery vehicles and associated launchers and facilities. To make use of these tools in a disarmament agreement, it would be necessary only to apply them in a more comprehensive manner. For example, the START Treaties specify procedures for verifiably eliminating certain types of strategic delivery vehicles and launchers: silos for intercontinental ballistic missiles (ICBMs), "heavy" ICBMs, mobile ICBMs and launchers, launch tubes for submarine-launched ballistic missiles (SLBMs), and heavy bombers. The START Treaties do not require the elimination of SLBMs, non-heavy silo-based ICBMs, and air-launched cruise missiles (ALCMs), however. Although having hundreds of such missiles in storage for possible redeployment may not be troubling at current levels of nuclear forces, this situation would be unstable at much lower levels. Moreover, aside from the INF Treaty's requirement that all ground-launched ballistic and cruise missiles with ranges between 500 and 5,500 kilometers be verifiably eliminated, there is no treaty requirement to limit or eliminate other non-strategic delivery systems, such as tactical aircraft and sea-launched cruise missiles (SLCMs). Both Russia and the United States have made unilateral pledges not to deploy certain types of non-strategic nuclear weapons and to dismantle some fraction of these, but such pledges are not comprehensive, legally binding, or subject to verification.[7]

Future arms control agreements should limit all nuclear delivery vehicles, regardless of range, and should require the elimination of all delivery vehicles withdrawn under the agreement. In some

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[7] On 27 September 1991, President Bush announced that all nuclear artillery and short-range missile warheads would be withdrawn and dismantled; that all naval tactical nuclear weapons would be removed from surface ships and attack submarines; and that all nuclear depth charges and older tactical nuclear bombs would be dismantled. On 5 October 1991, President Gorbachev announced that all nuclear artillery and non-strategic missile warheads would be dismantled; that all naval tactical nuclear warheads would be removed from surface ships and attack submarines; and that all nuclear warheads for surface-to-air missiles and ground-based naval aircraft would be placed in central storage. Gorbachev also promised to dismantle some fraction of the removed naval and surface-to-air missile warheads, and challenged the United States to agree to dismantle all naval nuclear weapons. Robert S. Norris, "Nuclear Notebook," *Bulletin of the Atomic Scientists* 47, no. 10 (December 1991): 49.

cases, the conversion to non-nuclear missions or peaceful applications might be permitted under strict guidelines and verification. For example, START I allows the conversion of nuclear bombers to conventional roles, provided that the converted bombers are based separately from nuclear bombers and at least 100 kilometers from nuclear-weapon storage sites, that they are modified so that they cannot carry nuclear armaments, and that they have observable differences from nuclear bombers of the same type.[8] A similar approach could be used to convert other types of nuclear delivery vehicles, such as tactical aircraft, ALCMs, and SLCMs, to conventional roles.[9] It also may be worthwhile to permit parties to retain small numbers of missiles for use as space launch vehicles (SLVs), subject to realistic projections of future demand, destruction of existing guidance systems, and ongoing monitoring. Although converted aircraft and missiles could be converted back into nuclear delivery vehicles, allowing the parties to verify that such systems are not equipped for nuclear delivery would be a useful confidence-building measure. Ultimately, however, verification would depend more on ensuring that the nuclear warheads for these systems had been eliminated.

An agreement to eliminate nuclear weapons should be accompanied by a global ban on ballistic missiles with ranges greater than 300 kilometers. Unlike manned aircraft and cruise missiles, longer-range ballistic missiles have little or no utility for the delivery of conventional munitions.[10] Only a handful of countries have deployed conventionally armed ballistic missiles with a range greater than 300 kilometers. Thus, it should not be difficult to obtain widespread support for a ban on ballistic missiles in the context of nuclear disarmament. Although SLVs are capable of being used as ballistic missiles, a variety of confidence-building measures could be adopted to minimize this danger.[11]

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[8] "To convert a heavy bomber so that it is no longer equipped for nuclear armaments, all weapons bays equipped to carry nuclear armaments shall be modified so as to render them incapable of carrying nuclear armaments. All external attachment joints for nuclear armaments and all external attachment joints for pylons for nuclear armaments shall be removed or modified so as to render them incapable of carrying nuclear armaments." (Article VI, paragraph 11, Protocol on Procedures Governing Conversion or Elimination.) In addition, non-nuclear bombers may not be based at air bases at which nuclear bombers are based. (Article V, paragraph 23, "Treaty Between the United States of America and the Union of Soviet Socialist Republics on the Reduction and Limitation of Strategic Offensive Arms," 31 July 1991.) Differences that make heavy bombers equipped for non-nuclear armaments distinguishable under START I from heavy bombers of the same type equipped for nuclear armaments may include: externally observable features of the fuselage, wing, landing gear, refueling devices, machine gun and cannon armament, and other structural differences; features of joints for attaching armaments and external launchers to the airplane; and features of the launchers, internal weapons bays, and joints for attaching weapons to the launcher.

[9] START I allows parties to deploy long-range non-nuclear ALCMs, but it does not specify the differences that would make non-nuclear ALCMs distinguishable from nuclear ALCMs, inasmuch as no long-range non-nuclear ALCMs had been deployed by either side. The Treaty does, however, give parties the right to inspect deployed non-nuclear ALCMs to verify that they are not armed with nuclear warheads, and to verify the features that distinguish them from nuclear ALCMs.

[10] For a discussion of the relative effectiveness of ballistic missiles and aircraft, see John R. Harvey, "Regional Ballistic Missiles and Advanced Strike Aircraft: Comparing Military Effectiveness," *International Security* 17, no. 2 (Fall 1992): 41–83; and Steve Fetter, "Ballistic Missiles and Weapons of Mass Destruction: What Is the Threat? What Should be Done?" *International Security* 16, no. 1 (Summer 1991): 5–42.

[11] For example, tests of SLVs in a ballistic trajectory could be prohibited, as could tests involving high-speed re-entry vehicles, or re-entry vehicles of a size and shape appropriate for the delivery of nuclear weapons. The total number of SLVs in storage or ready for launch could be restricted, as could the number of launch pads. In addition, payloads could be

Nuclear Weapons

Ironically, US–Russian efforts to control nuclear weaponry largely have ignored their most fearsome components—the nuclear explosives themselves. The reasons for this are easy to understand. Nuclear warheads are small, typically weighing a few hundred pounds; several could fit in an ordinary garage. They are assembled, transported, stored, repaired, and dismantled entirely under cover. National intelligence is incapable of counting an adversary's warheads with any accuracy; US estimates of the number of Russian warheads have an uncertainty of plus or minus 5,000 warheads.[12] Cooperative means of verification have been resisted, primarily because of concerns that they would reveal sensitive information about the design of nuclear weapons or the status of nuclear forces.

This attitude has begun to change recently. In September 1994, Presidents Clinton and Yeltsin agreed to exchange data on their countries' nuclear arsenals, and instructed their experts to meet to discuss what information could be provided to the other side. Such an agreement has not yet been reached, and the parties are likely to begin with a modest exchange of information. Preparations for nuclear disarmament, however, would require a comprehensive declaration, including:

- the location, type, status, and serial number of all nuclear explosive devices;

- the location, status, and description of facilities at which nuclear explosives had been designed, tested, assembled, stored, deployed, maintained, modified, repaired, and dismantled;[13] and

- the location, status, and description of facilities that produced key nuclear weapon components, such as high-explosive assemblies, detonators, neutron generators, and arming, fusing and firing sets; and of facilities that produced or fabricated special warhead materials, such as plutonium, highly enriched uranium (HEU), tritium, enriched lithium deuteride, and beryllium.[14]

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inspected to confirm the absence of nuclear weapons.

[12] In 1992, the CIA estimated that Russia had 30,000 nuclear weapons, "plus or minus 5,000." (See "Testimony of Lawrence Gershwin before the House Defense Appropriations Subcommittee," 6 May 1992.) Subsequent statements by Russian Minister of Atomic Energy Victor Mikhailov that the Russian stockpile peaked at 45,000 warheads cast doubt on the CIA estimate and emphasized further the difficulty of estimating warhead stockpiles with national intelligence alone.

[13] In the United States, this would include the design laboratories at Los Alamos, Livermore, and Sandia; the test sites in Nevada, Alaska, and Johnston Atoll; the Pantex plant, where weapons were assembled, inspected, maintained, and dismantled; and various Department of Defense storage and deployment sites.

[14] In the United States, this would include the Rocky Flats plant, where plutonium pits were fabricated; the Y-12 plant at Oak Ridge, where HEU and lithium deuteride components were fabricated; the Savannah River plant, where tritium was produced and loaded into bottles; Mound Laboratory, which produced detonators and firing sets; Pantex, which produced high-explosive assemblies; the Pinellas plant, which produced neutron generators and other electronic components; and the Kansas City (Bendix) plant, which produced various electronic, metal, and plastic components for nuclear weapons. See Thomas B. Cochran, William M. Arkin, Robert S. Norris, and Milton M. Hoenig, *Nuclear Weapon Databook, Vol. III: U.S.*

Such information would allow parties to verify the current status of nuclear stockpiles and nuclear-warhead production complexes, as a basis for verifying the dismantling of warheads and the decommissioning of related facilities. To provide confidence that this information was complete, it also would be helpful to have complete information about the history of the stockpiles, including:

- the history of each nuclear explosive device, including the dates of assembly, movement between various declared facilities, and its dismantling, destruction in an explosive test, or accidental loss; and

- the operating records of the warhead-related facilities listed above.

The United States has kept excellent records on its nuclear weapons, and it is reasonable to assume that the other nuclear-weapon states have as well. Substantial effort might be required to compile in a central database information from the various laboratories, production facilities, government agencies, and branches of the armed services, and to resolve any discrepancies that arise, but this would be well worth the trouble.

A data exchange could help build confidence between the parties even before the accuracy of the data was verified. An early exchange of data is particularly important because it would force governments to make decisions about compliance with reporting requirements well in advance of possible disarmament agreements.[15] A government that possesses thousands of nuclear weapons and has made no near-term commitment to disarmament is less likely to be suspected of falsifying records or hiding weapons than a country that has few weapons and is obliged to eliminate the remainder, simply because a country with thousands of warheads would have little incentive to cheat.

It is also important to begin verifying declarations as far in advance of a disarmament agreement as possible. As the number of nuclear weapons falls into the hundreds, states would be far more likely to have confidence in a declaration whose accuracy had been verified for years and for tens of thousands of nuclear warheads, than one whose verification had begun recently and only after thousands of warheads had been dismantled. Failure to verify the dismantling and consolidation of the huge US and Russian nuclear stockpiles could undermine severely the two sides' confidence in declarations made later about much smaller numbers of weapons. There is little pressure for warhead-verification measures today because current and planned stockpiles are so large as to make existing uncertainties unimportant. But unless the nuclear powers begin now to describe and verify their warhead stockpiles, when the need for verification is not pressing, they will have failed to lay a foundation that is strong enough to bear the weight of a disarmament regime.

Nuclear Warhead Facility Profiles (Cambridge, MA: Ballinger, 1987).

[15] For a review of arguments for and against an early exchange of information on nuclear weapon stockpiles, see Harald Mueller, "Transparency in Nuclear Arms: Toward a Nuclear Weapons Register," *Arms Control Today* 24, no. 8 (October 1994): 3–7.

Data on the history of stockpiles and the operation of warhead-related facilities cannot be verified directly, of course, but it could be checked for internal consistency, and for its consistency with archived intelligence data. If, for example, US satellites had detected the movement of nuclear warheads from a particular Russian facility on a particular date in the past, this could be checked against the records exchanged between the two countries. Indeed, such records should improve the value of archived data by confirming or contradicting past interpretations by intelligence agencies. The fact that countries would not know what intelligence information might be available would act as an incentive to provide complete and accurate data.

As with declarations on delivery vehicles, data on the current status of nuclear warheads would be verified by regular and short-notice inspections of declared facilities, combined with challenge inspections to verify the absence of warheads at other locations. For example, inspectors could count the number of warheads in a particular storage bunker and compare this to the number listed in the data exchange.

Unlike verification of missiles or silos, however, warhead verification raises the question of how inspectors could be sure that objects declared to be warheads were authentic. Without such assurances, parties might fear that fake warheads had been substituted for real ones, with the real warheads hidden to avoid dismantling. Simple radiation detectors could confirm the presence of fissile materials, but not necessarily the authenticity of a nuclear device.

One possibility would be to use a combination of radiation and other distinctive signatures to "fingerprint" types of nuclear warheads.[16] Either the country being inspected or the inspecting party, using information in the data exchange, could select a nuclear warhead of a particular type to be submitted for fingerprinting. Detectors then could measure the rate at which gamma rays and neutrons were emitted from the device at several locations, and possibly the transmission of gamma rays or neutrons from an external source; the size, weight, and heat output also could be measured. A signature with such detail would be extremely difficult to spoof, but it might raise concerns that sensitive design information was being revealed. To deal with such concerns, the information could be encoded in such a way that the inspection instrument would give only a "yes" or "no" answer when inspecting a particular device. Such a system is being developed by the United States to verify the authenticity of plutonium pits held in storage facilities. The use of statistical sampling procedures could minimize the number of warheads that would need to be authenticated. After authentication, warheads or warhead containers could be fitted with tamper-revealing seals; warheads with intact seals would not have to be authenticated again.

During such inspections, it also would be necessary to assure that other, undeclared objects do not contain warheads. If the object was not too large, gamma-ray and neutron detectors could

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[16] A possible scheme is described in Thomas B. Cochran and Steve Fetter, "Verifying the Authenticity of Nuclear Warheads without Revealing Sensitive Design Information" (Paper presented at the Third International Workshop on Verified Storage and Destruction of Nuclear Warheads, Kiev, 16–20 December 1991).

confirm the absence of fissile materials. Large objects could contain enough shielding to prevent such detection in a reasonable amount of time, however, in which case the inspected party should be required to use other methods to demonstrate that no warheads were contained within.

Verification of the declaration would be enhanced and simplified if all declared nuclear warheads were equipped with a unique identification number or "tag" that was specified in the declaration. A tagging scheme could use existing serial numbers or surface features, or it could use several different kinds of applied tags, such as bar-coded labels or plastic holographic images, overlaid by a tamper-proof tape.[17]

By allowing inspectors to confirm the presence of a particular warhead, tags would provide several advantages. First, tags would simplify verification, because the discovery of an untagged warhead would be prima facie evidence of a violation. Second, tags would allow random sampling to be used to verify declarations, thereby decreasing monitoring effort, cost, and intrusiveness.[18] Third, tags would allow particular warheads to be tracked as they moved among facilities. If combined with "perimeter-portal" monitoring, tags would allow the declaration to be updated continuously, and would foreclose the possibility that untagged warheads could make use of declared facilities. A nation intending to cheat would be forced to develop a parallel, clandestine system to store, maintain, repair, or deploy illegal warheads—thus increasing the cost of cheating and the risk of exposure.

Perimeter-portal systems are conceptually simple. A monitored perimeter—for example, a fence equipped with intrusion sensors and patrolled by inspectors—would be installed around facilities where nuclear warheads were kept. The perimeter would contain a small number of portals or gates that would be equipped to detect the passage of a warhead into or out of the facility. Thus, nuclear warheads could not enter or be removed from declared facilities without detection.

The consolidation of warhead stockpiles in the United States and Russia should reduce greatly the cost of installing and operating perimeter-portal systems. One could begin perimeter-portal monitoring with a single storage facility for warheads slated for dismantling. The next logical step would be to install such systems at other storage facilities, dismantling facilities, and finally at facilities where warheads are deployed.

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[17] Annex 6 of the Inspection Protocol of the START I treaty defines a unique identifier as "a non-repeating alpha-numeric production number, or a copy thereof, that has been applied by the inspected Party, using its own technology."

[18] Without sampling, inspectors would have to count every warhead at a site, and possibly verify the authenticity of each warhead. Sampling could greatly reduce the number of warheads that would be examined. For example, a detailed inspection of only 28 randomly selected warheads would provide 95 percent confidence that at least 90 percent of these warheads were authentic (or that the number of warheads did not exceed the declared number by more than 10 percent). In addition, there would be only a 25 percent chance that a 5 percent violation would escape detection (i.e., 50 of 1000 warheads were phony or undeclared), and a 1 percent chance that a 15 percent violation would go undetected. Even a 1 percent violation would have a 25 percent chance of detection.

The monitoring of assembly and dismantling facilities deserves special attention. Unlike the dismantling or destruction of delivery vehicles and launchers, the dismantling of nuclear warheads cannot be verified directly without revealing sensitive design information. It is, for example, highly unlikely that Russia would allow US (or British, French, or Chinese) inspectors to observe the disassembly of its warheads.

The most straightforward solution would be to install perimeter-portal systems at dismantling facilities, and to monitor the flow of nuclear weapons into the facilities and the flow of plutonium pits out.[19] A particular nuclear weapon would be counted as dismantled when the corresponding pit had been placed in monitored storage. If desired, pits could be "fingerprinted" and associated with particular weapon types. At specified intervals, all the weapons within the facility could be dismantled and interior inspections allowed to verify that a stockpile of weapons had not been accumulated within the facility.

A possible complication is the fact that assembly and stockpile maintenance activities usually take place in the same facility as dismantling occurs. Even at very low levels of nuclear weapons, warhead remanufacturing and maintenance would cease only when a decision had been made to dismantle all remaining nuclear weapons. To simplify monitoring before such a decision, it might be possible to segregate remanufacturing and maintenance from dismantling activities by using different perimeters and portals for the different functions even if they were carried out within the same facility. In either case, it would be necessary to ensure that bogus warheads were not entering the facility, and that any pits entering the facility (e.g., for remanufactured warheads) were accounted for. Otherwise, it might be possible for a nation intending to cheat to inflate the number of warheads being dismantled, or to build entirely new warheads under the guise of remanufacturing.

For example, assume that the assembly and dismantling facility had a single portal through which all materials must enter or exit. Entering the portal would be warheads for dismantling; warheads for examination, maintenance, repair, or remanufacture; and new pits, fresh tritium bottles, high-explosive assemblies, and other components for stockpile maintenance activities. Exiting the facility would be reconditioned warheads and pits and other components from the dismantled and reconditioned warheads. Inspections at the portal would ensure that objects declared to be warheads or pits of a particular type were authentic, and that no warheads or pits entered or exited the facility without being detected and accounted for. There would then be a balance between warheads entering the facility for dismantling and pits of the corresponding type exiting the facility; and between warheads of a particular type (and associated warhead components) entering and exiting the facility for stockpile maintenance activities. Because this balance would not necessarily be exact during

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[19] Such a scheme is described in Theodore B. Taylor and Lev P. Feoktistov, "Verified Elimination of Nuclear Warheads and Disposition of Contained Nuclear Materials," in *Verification: Monitoring Disarmament*, ed. Francesco Calogero, Marvin L. Goldberger, and Sergei P. Kapitza (Boulder, Colo.: Westview Press, 1991), 45–66. See also Theodore Taylor, "Technological Problems of Verification," in *A Nuclear-weapon-free World: Desirable? Feasible?* ed. Joseph Rotblat, Jack Steinberger, and Bhalchandra Udgaonkar (Boulder, Colo.: Westview Press, 1993).

dismantling or maintenance campaigns, the facility's inventory of warheads and pits would have to be taken at increasingly frequent intervals as warhead levels were decreased.

Regarding warhead components, various levels of accounting, control, and recycling could be permitted:

- Plutonium pits, which are the most expensive and difficult components to produce, should receive the same degree of accounting and control as the warheads themselves. Pits from dismantled warheads should be stored and ultimately converted for disposal or for peaceful use under international safeguards. So long as nuclear stockpiles were permitted, pits from remanufactured warheads could be recycled for use as new pits. Perimeter-portal controls should be placed around facilities for fabricating pits.

- So long as nuclear stockpiles were permitted, tritium from both dismantled and remanufactured warheads would be recovered and recycled; thereafter tritium would be used only for peaceful purposes under international safeguards.

- The manufacture of other important warhead components, such as high-explosive implosion assemblies, neutron generators, and fusing and firing systems, should be reported, and perhaps subject to inspection.

The nuclear-weapon states already have begun to close a number of facilities that were used previously to produce materials and components for nuclear weapons. The consolidation of nuclear weapon complexes will continue as nuclear stockpiles decline. Facilities no longer needed for weapons should be dismantled or converted to peaceful use. Close-out inspections and periodic follow-on inspections would verify the cessation of all weapon-related activities at such facilities. As the number of nuclear weapons approached zero, all facilities listed in the initial declaration would be closed out.

In all of these procedures, nuclear-weapon states would have to balance the desire for effective verification with the need to protect sensitive nuclear-weapon design information. Initially, this balance might be served best by having the United States and Russia inspect each other. As the number of nuclear weapons drops, the other three nuclear-weapon states could be invited to join the process on a more-or-less equal basis. At some point, verification would be the responsibility of the IAEA or some other international agency, perhaps using nationals from the nuclear-weapon states for more-sensitive tasks.

Fissile Materials

Fissile materials—highly enriched uranium and plutonium—are the essential ingredients of all nuclear weapons.[20] They are also the most expensive ingredients.[21] Control and accounting for these materials therefore must be a fundamental element of any comprehensive disarmament regime, just as it is the basis for the current non-proliferation regime.

As with delivery vehicles and warheads, the first step would be a declaration of existing stockpiles of all fissile materials. In this case, parties would declare:

- the mass, chemical and isotopic composition, status (in weapons or weapon components, storage, fresh or spent reactor fuel, or wastes), and location of all fissile materials;
- a description of all facilities that had been used to produce fissile materials;[22]
- the production records and a material balance for each facility;
- an account of fissile materials otherwise acquired (e.g., from foreign countries); and
- an account of all fissile materials removed from the inventory (e.g., consumed in weapon tests or nuclear reactors, dispersed in accidents, lost to waste or radioactive decay, or transferred to other countries).

There are two major differences between this declaration and those previously described. First, record keeping in all countries is better and more accurate for missiles and warheads than for fissile materials. Second, missiles and warheads are subject to simple item accounting; fissile materials are not. Material accounting is subject to errors of measurement and estimation. Although the mass of a finished piece of plutonium or uranium metal can be measured with high accuracy, the amount of material that remains in inaccessible locations within a facility or that is lost to waste streams at various stages of production and processing often is not (and often cannot be) measured accurately.

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[20] Fissile materials are those that can sustain a fast-fission chain reaction, and therefore can be used as the basis for a fission explosive. All nuclear weapons contain fission explosives; no weapons rely on fusion alone. Plutonium and HEU (uranium containing more than 20 percent uranium 235 [U^{235}]) are the most common fissile materials. Other fissile materials exist but are not known to have been used in nuclear weapons. The controls described in this section would apply to these less-common materials as well.

[21] The production of fissile materials accounted for about 90 percent of the $25 billion spent by the United States on the Manhattan Project, when its costs are expressed in 1995 prices. Materials production accounted for about 50 percent of the $380 billion spent by the United States on nuclear warhead research, development, testing, and production overall. (Kevin O'Neill, "Nuclear Materials Production.")

[22] In the United States, this would include the uranium enrichment facilities at Oak Ridge, Paducah, and Portsmouth; the plutonium-production reactors and reprocessing plants at Hanford and Savannah River; the Idaho reprocessing plant; the commercial reprocessing plant at West Valley; and various facilities for purifying and chemically converting natural uranium into forms suitable for enrichment or fuel fabrication.

It is likely that the nuclear weapon states know, with very little uncertainty, how much plutonium and HEU are in their fabricated weapon components (pits and secondaries), fresh fuel rods, and various storage forms (e.g., metal "buttons" and cans filled with oxide). More problematic is the plutonium and HEU in spent fuel; in metal scraps; in powders lining pipes, glove boxes, and ventilation ducts; and in various liquid solutions and wastes. A recent accounting of US plutonium stockpiles revealed that, of the 111.4 metric tons of plutonium produced or otherwise acquired by the United States, nearly 3.4 tons is estimated to have been lost to waste.[23] Such estimates, however, are subject to large uncertainties, as is illustrated by the fact that the total amount of plutonium actually in wastes is estimated at 3.9 tons. Accounting for plutonium losses probably is much less accurate in Russia.

Estimates of national inventories may contain uncertainties of a few percent. For example, the best estimate of the total amount of plutonium produced or otherwise acquired by the United States is 2.8 tons higher than the measured amount of plutonium in current stockpiles (99.5 tons) plus the estimated amount removed from the inventory in tests, wastes, reactors, decay, accidents, and transfers (9.1 tons).[24] This 2.8 tons is the sum of inventory differences at a dozen government facilities over fifty years. There is no evidence that any of this plutonium was lost or stolen. Most, if not all, of the inventory difference 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. In the latter case, a significant fraction of the "missing" plutonium may be recovered as facilities are decommissioned and decontaminated.

Inventory differences are likely to be even larger for US production of HEU, because the United States did not measure how much HEU went into waste streams and did not keep precise records of the enrichment of various product streams. In addition, Russian and Chinese production records probably are considerably less dependable than those of the United States. Although concerted efforts could be made to minimize inventory differences, it seems unlikely that they could be reduced below several percent of the total inventory.

The large uncertainties in fissile-material inventories could prove to be the largest obstacle to verifying nuclear disarmament. As Table 1 indicates, the amount of fissile materials reserved for military use in the nuclear-weapon states is huge. An uncertainty of five percent in the US or Russian stockpiles corresponds to enough material to build about 5,000 nuclear explosives; in the case of the United Kingdom, France, or China, about 100 nuclear explosives; in the case of Israel or India, about

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[23] "Plutonium: The First 50 Years" (Washington, DC: US Department of Energy, February 1996). One metric ton is equal to 1000 kilograms or 2200 pounds.

[24] Ibid.

5 explosives. To this challenge we also must add the difficulty of accounting for hundreds of tons of civilian fissile materials (mostly plutonium) in these states that has not been safeguarded by the IAEA.[25]

Table 1

Estimated amount of military fissile materials in the nuclear-weapon and threshold states, and the corresponding number of nuclear explosives that could be built with this material.

Country	Plutonium (tons)	HEU (tons)	number of explosives*
Russia	120	1000	100,000
United States	100	700	90,000
France	6	15	3,000
China	3	15	2,000
United Kingdom	2.6	13	2,000
Israel	0.4	---	100
India	0.4	---	100
Pakistan	---	0.2	20
Total	230	1700	200,000

Source: Frans Berkhout, Oleg Bukharin, Harold Feiveson, and Marvin Miller, "A Cutoff in the Production of Fissile Material," ***International Security*** 19, no. 3 (Winter 1994/95): 174.

*Assumes 4 kilograms of plutonium or 12 kilograms of U^{235} for each fission explosive.

It would be fairly straightforward, if time-consuming, to verify the accuracy of some categories of information provided in a fissile-material data exchange. For example, inspectors could verify, using standard assay and sampling techniques, that selected canisters contained material of the

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[25] By 2000, the nuclear-weapon and threshold states will have produced about 750 tons of plutonium in civilian reactors. Of this, about 180 tons will be separated; the remainder will be contained in spent fuel. Although most of this material will be available to the IAEA under the voluntary safeguards agreements between the nuclear-weapon states and the IAEA, very little will actually be under IAEA safeguards. David Albright, Frans Berkhout, and William Walker, *World Inventory of Plutonium and Highly Enriched Uranium—1992* (New York: Oxford University Press, 1993), 109–111.

The plutonium discharged from civilian power reactors contains a higher fraction of certain undesirable isotopes (Pu^{240} and Pu^{241}) than does the "weapon-grade" plutonium produced in dedicated military production reactors. These undesirable isotopes produce large amounts of neutrons and heat, complicating bomb design and leading some observers to argue that "reactor-grade" plutonium is unsuited for weapons. The nuclear-weapon states, however, would be quite capable of building effective weapons using reactor-grade plutonium. Indeed, any state or group that could make a nuclear explosive with weapon-grade plutonium probably could make an almost equally effective device with reactor-grade plutonium. See J. Carson Mark, "Explosive Properties of Reactor-grade Plutonium," *Science & Global Security* 4, no. 1 (1993): 111–128.

amount and isotopic composition specified in the declaration. In some cases, such as scraps and wastes, verification will be complicated by physical barriers, safety considerations, and measurement uncertainties. Other information, such as the amount and composition of fissile materials in a particular type of warhead, likely would remain unverified. Of course, as disarmament proceeds, weapons will be dismantled and the pits and other components they contain will be physically or chemically converted to forms appropriate for disposal or peaceful use under international safeguards, as will materials recovered during the clean-up and decommissioning of production and fabrication facilities. At the final stage of nuclear disarmament, more precise measurements could be made and compared with the initial declarations. The prospect that such data eventually would be subject to verification would be a powerful incentive to give accurate declarations at earlier stages.

One problem is that this final stage of disarmament might come decades after the delivery vehicles and warheads had been dismantled. The United States, for example, currently does not have a facility to process plutonium pits and has no plans to build one. A decision to build such a facility probably will await a final decision on the ultimate disposition of the plutonium—a decision likely to be delayed by legal challenges, political maneuvering, and substantial economic costs. The clean-up of production and fabrication facilities also will take decades to complete. A full accounting of fissile-material stockpiles is therefore likely to lag considerably behind the rest of the disarmament process.

But even if one could measure precisely the amount of material in the various forms enumerated in the declaration, there would remain the more difficult problem of ensuring that there were no undeclared stocks of material. This would be accomplished primarily by confirming declarations about the total amount of material that had been produced, but, as noted above, it is unlikely that it will be possible to confirm such declarations with an uncertainty of less than five or ten percent.

To understand these uncertainties, consider how one might verify the amount of HEU a country had produced. Natural uranium contains only 0.7 percent of the fissile isotope U^{235}; the remaining 99.3 percent is non-fissile U^{238}. Nuclear weapons require highly enriched uranium, typically containing more than 90 percent U^{235}. To produce HEU, uranium is mined, purified, converted into uranium hexafluoride gas, and shipped to an enrichment plant. Enrichment plants separate the isotopes by passing uranium gas through thousands of stages, each of which increases very slightly the concentration of U^{235}. For every 1,000 kilograms of natural uranium fed into the plant, about 5 kilograms of weapon-grade HEU and 995 kilograms of depleted uranium are produced.[26] Depleted uranium, which has little value, is usually stored at the enrichment facility in metal cylinders. A single plant often produced uranium of various enrichments for weapons and reactor fuel.

Verifying declarations of HEU production would begin with a material balance for each enrichment facility. Recorded receipts of uranium hexafluoride would be compared with shipments

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[26] This examples assumes that the HEU product is 90-percent U^{235}, and that the depleted uranium tails contain 0.26 percent U^{235}.

of enriched product and discharges of depleted uranium. In addition to the total amount of uranium, a mass balance would be done for U^{235}, based on recorded isotopic assays of enriched and depleted material. The overall design and enrichment capacity of each plant would be verified though on-site inspections. Records of the total amount of separative work performed by the plant would be compared with its design capacity, the amounts and enrichment levels of product and tails, and, in the case of gaseous diffusion plants, records of electricity consumption. As an added check, the total amount of uranium mined or imported could be compared with the amount used as feed for enrichment plants, taking into account other demand for natural uranium. The production of low-enriched uranium also could be compared with records of fuel fabrication and reactor fuel loadings. Even if records were complete and accurate, however, uncertainties of at least several percent could be expected in estimates of the amount of HEU produced.

Plutonium, which does not exist in nature, is produced in nuclear reactors when U^{238} absorbs neutrons. Nearly all of the plutonium used in weapons has been produced in special-purpose “production” reactors. The plutonium accumulates in the uranium fuel or targets over a period of several months, along with intensely radioactive fission products. The uranium fuel rods and targets are discharged from the reactor and shipped to a reprocessing facility where they are dissolved and the plutonium and uranium are separated from the fission-product wastes.

Verifying plutonium production would involve examining records of the fabrication of uranium fuel and target rods for plutonium-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 and chemical flowsheet of the reprocessing plants; monthly production of plutonium product; and the volume, isotopic concentrations, and disposition of the various waste streams. If the records were complete and accurate, this information would allow plutonium production to be estimated with an uncertainty of perhaps five percent.

The value of this method of verifying production declarations would depend almost entirely upon the accuracy, completeness, and authenticity of the records that were provided. One could check that operating records were consistent with declarations, and that the records were internally consistent, but this should not be confused with independently verifying their accuracy.

First, records can be falsified. While it is not a simple matter to invent a false operating history that is internally self-consistent in all respects, it could be done by a group that was familiar with the production facilities. The authenticity of old records kept on paper could be verified using forensic techniques, but original records might have been lost or destroyed and might have to be reconstructed.[27] Moreover, some countries may keep records in computer files, which could be

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[27] Old operating records were probably kept on paper, the authenticity of which could be determined by examining the composition of the paper and/or ink as well as the nature of the instrument that applied the ink to the paper. The number of paper mills in a given country is limited, and the composition of the fibers in the paper changes with time, as does the composition of ink. If the United States had samples of documents from the time period in question on file, they could be compared with the production records. Moreover, production records may contain the signature of some official, which also

altered by the host nation without detection. If a nation wished to hide the production of some quantity of HEU, for example, it could "doctor the books" to delete the uranium feed and separative work required to produce the material, or to show instead the production of an amount of low-enriched uranium that would have consumed an equivalent amount of uranium and separative work.

Second, even authentic records may be 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 bombs as quickly as possible. Although record-keeping probably was good for militarily important materials, such as plutonium and HEU, it is less likely that good accounts were kept for natural or depleted uranium or reprocessing wastes. And one cannot exclude the possibility that even authentic records were falsified. For example, operators of Soviet facilities, operating under a quota system, may have understated output when production exceeded the yearly quota, storing the surplus to guard against the possibility of shortfalls in future years. Attempts to correct such poor or inaccurate record-keeping, moreover, might trigger suspicions that records had been falsified to hide material.

Thus, it is possible that declarations would be treated with suspicion, and that examination of operating records would fail to resolve (or might even reinforce) such doubts. In these cases, it would be helpful to have recourse to physical evidence that could dispel or support such suspicions, and embolden the international community to take appropriate actions if the suspicions proved warranted.

Production facilities are possible sources of such physical evidence. Although the design capacity of existing facilities can be verified by on-site inspections, the capacity of a particular plant may have changed dramatically over time, and some facilities (e.g., British and Soviet gaseous diffusion plants) already have been dismantled. Even if the design of a plant was known, this would serve only to establish an upper bound on material production. Actual production is often well below the theoretical capacity of a plant for a number of reasons, including routine maintenance, overhauls and upgrading, accidents, safety concerns, labor disputes, shortage of inputs, or lack of demand for outputs. Independent evidence of a pause or decrease in production may be difficult to come by.

Less ambiguous sources of physical evidence that could be used to verify production declarations may exist, however.[28] In plutonium-production reactors, for example, the ratio of isotopes in permanent components of the reactor (e.g., the graphite moderator, steel fuel supports, or reactor vessel) may provide a fairly accurate estimate of the total thermal energy, and therefore the total amount of plutonium, produced during the reactor's lifetime.[29] Although estimates derived

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may be compared with other samples.

[28] Steve Fetter, "Nuclear Archaeology: Verifying Declarations of Fissile-material Production," *Science and Global Security* 3, nos. 3–4 (1992).

[29] T. W. Wood, D.C. Gerlach, B.D. Reid, and W.C. Morgan, "Feasibility of Isotopic Measurements: Graphite Isotopic Ratio Method" (April 1994).

in this way would be uncertain by perhaps ten percent, they would be largely independent of record-keeping by the host country, and therefore would provide an independent check on the declaration. In the case of uranium enrichment facilities, isotopic ratios in depleted uranium stored on site could confirm records of product and tails assays over a particular time period. Even these types of measurements are not foolproof, however: production reactors might be dismantled before measurements could be made, and depleted uranium could be hidden or used for other purposes (e.g., ballast, bullets, or blending stock).

South Africa: A Case Study in Disarmament

South Africa is the only country known to have crossed the nuclear threshold in both directions. Having built six Hiroshima-type nuclear bombs during the 1980s, South Africa decided in the early 1990s to dismantle its weapons and join the nuclear Non-Proliferation Treaty (NPT) as a non-nuclear-weapon state. South Africa's experience in convincing the international community that it had disarmed is therefore particularly instructive about the promise and problems of verifying disarmament.

Beginning in July 1990, South Africa disarmed in secret, presumably so that it would not have to reveal that it had built a small nuclear arsenal. Within a year, the nuclear bombs had been dismantled, documents destroyed, production and assembly facilities decommissioned, and HEU weapon components cast into standard shapes for storage and international inspection.[30] South Africa acceded to the NPT in July 1991.

Only in March 1993 did President de Klerk announce that South Africa had built six nuclear bombs. The South African government apparently had concluded that domestic and international confidence in South Africa's non-nuclear status would be enhanced if a complete disclosure of the program was made. 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 was briefed on the design and production of the bombs, and then verified that six bombs-worth of HEU had been placed under safeguards, confirmed that other components had been rendered unusable for weapons, and ensured that weapon-related activities had ceased at various facilities.

IAEA inspectors easily verified that *declared* weapons and facilities had been dismantled and decommissioned, and that the *declared* stocks of HEU had been placed in safeguarded storage. Verifying that South Africa had dismantled *all* of its weapons and placed *all* of its HEU under safeguards was considerably more difficult, however. This is, of course, the central problem in verifying nuclear disarmament—achieving adequate confidence that not a single weapon or significant quantity of fissile materials has been hidden.

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[30] David Albright, "South Africa's Secret Nuclear Weapons," *ISIS Report*, May 1994.

In the South African case, the major problem was verifying the accuracy and completeness of South Africa's declaration of the amount of HEU it possessed. South Africa claimed that the Valindaba enrichment plant had produced considerably less HEU than its design capacity would have allowed, primarily, the South Africans stated, because accidents caused plant shutdowns, and because the plant also was used to produce low-enriched uranium for reactor fuel. These claims were supported by operating records and statements by plant officials, but some observers treated the South African declaration with skepticism.

In the end, the IAEA concluded that "the amounts of HEU which could have been produced by the pilot enrichment plant are consistent with the amounts declared."[31] This conclusion was based largely on an analysis of the original, handwritten operating records of the plant, which were provided to the Agency and which the IAEA judged to be authentic. Estimates of the amount of enriched uranium produced by the plant based on these operating records and the plant's specifications matched the South African declaration within an acceptable margin of uncertainty.[32] A material balance of the plant, however, revealed much greater uncertainties because plant operators kept poor records of the enrichment of the depleted-uranium tails.[33] Although an assay of the 370 tons of tails, which are stored on-site in some 600 cylinders, would have reduced greatly the uncertainty in the material balance, the IAEA decided that the increased confidence provided by such measurements would not justify their considerable expense.[34]

The lessons of the South African experience for verifying nuclear disarmament are both positive and negative. On the positive side, the experience suggests that when a government makes a full and complete disclosure of past nuclear activities; offers international inspectors unfettered access to all relevant facilities, records, materials, and personnel; and cooperates fully with the investigation to resolve any discrepancies that may arise, the international community can gain considerable confidence in a government's claim that it had disarmed. This conclusion should, however, be tempered by the unique situation of South Africa. Unlike other nuclear-armed countries,

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[31] Quoted in Albright, "South Africa's Secret Nuclear Weapons."

[32] The acceptable margin was one significant quantity, or 25 kilograms of HEU. See Albright, "South Africa's Secret Nuclear Weapons," and Office of Technology Assessment, *Nuclear Safeguards and the International Atomic Energy Agency*, OTA-ISS-615 (Washington, DC: U.S. Government Printing Office, June 1995), 85.

[33] The mass of U^{235} fed into an enrichment facility should precisely equal the mass of U^{235} in the enriched product plus the mass of U^{235} in the depleted tails, plus the mass of U^{235} lost in wastes or environmental releases. In the South African case, however, estimates of the amount of U^{235} fed into the plant substantially exceeded the amount estimated to have exited the facility as product, tails, and waste. This could indicate either diversion or poor accounting. Although the concentration of U^{235} in the feed and product were measured with reasonably high accuracy, South Africa kept poor records of the concentration of U^{235} in the tails, leading to substantial uncertainties in the total mass. These uncertainties could have been reduced substantially by measuring the concentration of U^{235} in the depleted uranium stored at the site, but this would have been expensive and time-consuming.

[34] See Thomas B. Cochran, "Highly Enriched Uranium Production for South African Nuclear Weapons," *Science and Global Security* 4, no. 2 (1994): 161–178; and Darryl Howlett and John Simpson, "Nuclearisation and Denuclearisation in South Africa," *Survival* 35, no. 3 (Autumn 1993): 154–173.

South Africa did not fear attack from adversaries armed with nuclear weapons or superior conventional forces. Indeed, the South African government's greatest concerns focused on an internal risk: maintaining control over nuclear weapons in the turmoil that might accompany the movement toward majority rule. That the South African government had little incentive to cheat on its pledge of nuclear disarmament was undoubtedly a major factor in building confidence in that pledge. The standard of verification required by the international community might be considerably greater for countries that are viewed as having powerful incentives to cheat, or in cases in which adversaries would have strong reasons to fear the possibility of cheating. This underscores the importance of viewing verification in its political context, and the need for other mechanisms to reduce incentives to cheat.

On the negative side, the South African experience shows the difficulty of verifying declarations of even small inventories of fissile materials. As noted by IAEA 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."[35] Although South Africa's nuclear program may have been substantial and sustained by IAEA standards, it was tiny and transient compared to those of the nuclear-weapon states. We can expect that, like South Africa, many nuclear-weapon states have not kept good records of certain parameters that, while valuable for verification, were not relevant for the production of materials and weapons. If the IAEA had difficulty in verifying the production of a few hundred kilograms of HEU in South Africa, how will it cope with stockpiles that are a thousand times larger? What if original records are not available or cannot be authenticated? What if production facilities have been dismantled, or plant managers are unavailable for interviews? These are difficult questions that will have to be addressed if disarmament is to be considered seriously.

How Confident Could We Be of Disarmament?

In the end, then, we come back to the fundamental question: "How confident could we be that states had disarmed?"

We could be certain that the nuclear-weapon states had eliminated the types of launchers that now dominate their strategic nuclear forces: ICBM silos and ballistic-missile submarines. Initially, there would be somewhat more uncertainty that all ballistic missiles and all launchers for mobile ICBMs had been eliminated, but these doubts soon would fade if the monitoring system did not detect evidence of hidden stockpiles. Although a stockpile of missiles or mobile launchers might escape detection if hidden in an ordinary warehouse, they soon would lose their military utility without the regular test, maintenance, and exercise activities, which would, if carried out, greatly increase the risk of exposure. This would be especially true if long-range ballistic missiles were banned and if the production of rocket components for space-launch vehicles was restricted and closely monitored.

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[35] Quoted in Howlett and Simpson, "Nuclearisation and Denuclearisation in South Africa."

Of more concern would be long-range aircraft, such as heavy bombers, tactical fighter-bombers, and cruise missiles. Even if we could verify that all nuclear-armed aircraft had been destroyed, conventional variants would exist and could be converted to deliver nuclear weapons with little or no warning. Of course, even civilian aircraft or ships could be pressed into service to deliver a hidden stockpile of nuclear bombs. Verifying nuclear disarmament therefore must rely on verifying that no hidden stockpiles of nuclear explosives exist.

We could be highly confident that a declared number of nuclear warheads had been dismantled if dismantling facilities and fabricated weapon components were subject to verification during the reduction process. Unfortunately, the process of dismantling excess warheads is already well underway in the United States and Russia without the benefit of any verification or transparency measures. As long as the pits remain intact, it may be possible yet to gain a high degree of confidence that a certain number of nuclear warheads were dismantled. If, however, the nuclear components are recast or reused, it will be impossible to verify independently the number or type of weapons that have been dismantled. In that case, one would have to rely primarily on records and assurances provided by the inspected party, supplemented by an imperfect accounting of the fissile materials that had been placed under safeguards.

A statement that *all* warheads had been dismantled would be even more difficult to verify, however, resting largely on the perceived accuracy and authenticity of records provided by the inspected party, the testimony of relevant officials, and political judgments about the disarming party's incentives to cheat. From a purely technical point of view, it would not be difficult to hide the existence of a few dozen (or perhaps even a few hundred) nuclear devices from inspectors. A nation could falsify records to show that the hidden warheads had never been assembled, or that they had been dismantled and that the fissile components had been melted down and used for other purposes. Alternatively, a country could claim that hidden warheads had been lost on sunken submarines or ships, or destroyed in airplane crashes or nuclear tests.[36] (Weapon-effects tests, in which several nuclear warheads are exposed to the radiation from a nuclear explosion but often are not destroyed, might be particularly convenient in this regard.)

A country with a hidden cache of bombs could be expected to limit knowledge of their existence to only a handful of the most trustworthy people. The infrastructure required to support and maintain a small arsenal need not attract attention or require significant amounts of money or special materials, particularly if the weapons had been selected or designed to minimize maintenance. The warheads themselves are small; several nuclear bombs or cruise-missile warheads could be transported in a common delivery truck and stored in any warehouse or basement. Only a small cadre of trained personnel would be required to examine the warheads from time to time for signs of aging

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[36] The United States and Russia have both lost nuclear-armed submarines at sea, and there would be no way to independently verify the number of weapons on board. Many US nuclear weapons were involved in aircraft crashes, although all of the weapons were recovered. Finally, dozens of US nuclear weapons were used, but probably not destroyed, in weapon-effects tests.

and deterioration; depending on their design, some components might have to be replaced every twenty or thirty years. Some weapons would require a fresh supply of tritium to give their design yield, but the required tritium could be diverted from civilian stocks only if and when the weapons were needed.[37]

Once hidden, it is unlikely that the warheads would be discovered unless someone aware of their existence leaked information about their location.[38] The probability of such a leak would depend mostly on the nature of the country's political culture. Governments vary in their ability to keep secrets, but none is perfectly transparent or perfectly opaque. The oppressive governments of Iraq and North Korea have suffered high-level defectors, while the relatively permissive government of the United States has been able to keep some important secrets for a remarkably long time. Nevertheless, it seems reasonable to assume that confidence in compliance would be much higher for countries with stable democracies that have demonstrated respect for the rights of individuals and the rule of law. Not only would such countries be less likely to cheat in the first place, but they also would be more likely to suffer a leak if they did cheat.

An added degree of confidence in the dismantling of nuclear arsenals would be obtained if all fissile materials appeared to have been declared and accounted for. At best, however, the inspection agency would be able to conclude that there was no evidence that materials had been hidden, that the declarations of amounts of materials produced and stockpiled were consistent with available records and physical evidence, and that any discrepancies were within the uncertainties inherent in the estimating procedure. Unfortunately, these uncertainties would be very large—at least several percent of the total amount of materials produced. A declaration that was verified to the best of our abilities would not prove, therefore, that weapon states had not hidden significant amounts of fissile materials—perhaps enough to make hundreds of warheads—from international inspectors.

The effect of surprise or "challenge" inspections on confidence in disarmament is generally positive, but not without qualification. That such inspections are possible should work to deter cheating and to increase confidence that countries are not cheating. Challenge inspection privileges should be exercised often, however, even in countries for which there were no suspicions of cheating, so that merely requesting such an inspection would not erode confidence in the regime. But challenge

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[37] A small accelerator also could be built to produce the small amounts of tritium that would be required. An accelerator with a beam power of 200 kilowatts, which could be built and operated clandestinely, would produce neutrons at a rate sufficient to maintain a 50-gram stockpile of tritium (enough for a dozen weapons).

[38] It is precisely for this reason—the inherent weakness of technical means of verification in detecting small violations—that some analysts stress the importance of "citizen reporting," "whistle-blowing," or "inspection by the people." (See, for example, Joseph Rotblat, "Societal Verification," in *A Nuclear-weapon-free World: Desirable? Feasible?*) While it is undoubtedly important to facilitate citizen reporting of treaty violations, it would be unwise to put too much faith in this process until the governments in question—particularly those of China and Russia, but also of India and Israel—attain the same degree of transparency and respect for international norms as those of the United States and other Organisation for Economic Co-operation and Development (OECD) countries. Even in the United States it is still possible to keep secret illegal activities for many years if the proper precautions are taken to restrict access to the information.

inspections could expose cheating only if the location of the illegal activity was known, and no conceivable inspection regime could search a significant fraction of all possible sites where hidden weapons or plutonium might be stored. If there were strong suspicions that a country was cheating, a series of premature and fruitless challenge inspections could be used by the cheater as evidence of its innocence. The cheater could claim, moreover, that it was the victim of a unjust crusade by UN officials or governments with ulterior motives. Cheaters might even plant incriminating evidence about locations where no illegal activities were occurring in order to minimize the probability of finding the real site. The fact that challenge inspections were permitted might make it difficult or impossible for the international community to respond to evidence of cheating if the hidden weapons were not found.

The passage of time may work to alleviate fears of cheating. If, for example, no evidence of cheating is uncovered during a decade of intensive monitoring and inspection, then confidence in disarmament may be increased substantially. Such increased confidence may be unfounded, however, because the cumulative probability of detecting a hidden stockpile of bombs may not increase much with time. As noted above, a well-designed program to hide a dozen nuclear weapons need not have any signature that would be observable by international inspectors or national intelligence. The very fact that it would be possible to hide such a program could erode confidence during times when political relationships sour for other reasons.

In short, one could never be certain that a country that had built a substantial nuclear arsenal had disarmed completely. It is highly unlikely that the United States or an international inspectorate would be able to prove beyond a reasonable doubt that Russia or China had not sequestered a dozen or so “bombs in the basement” (or enough plutonium to build a dozen bombs), short of administering truth serum or polygraph tests to the nation’s highest political and military leaders. But this conclusion, while important, is intuitively obvious. The more important question is whether the theoretical possibility of cheating makes disarmament impossible in practice.

No treaty is perfectly verifiable. Fortunately, perfection is not an appropriate standard. A verification regime can reduce the likelihood of cheating only by making it costly and risky, and by diminishing the magnitude of cheating that could go undetected. It cannot make undetected cheating impossible. Ultimately, the United States must judge whether the benefits of nuclear disarmament outweigh the risks of possible cheating. The risks of cheating depend far less on the characteristics of the verification regime than on the probability that states that disarm might become hostile, on the perceived value of small numbers of nuclear weapons in securing the goals of such hostile states, and on the precautions that the United States had taken, together with other states, to protect against the possibility of cheating.

Detecting Rearmament

Besides verifying that all nuclear weapons had been dismantled and that all fissile materials had been placed under international safeguards, the verification regime would have to be able to provide timely warning of any attempt to build new nuclear weapons or to reconstruct dismantled nuclear arsenals.[39] In contrast with verifying disarmament, the international community already has considerable experience with verifying that countries are not building nuclear weapons, at least with respect to the non-nuclear-weapon states that are parties to the NPT. Much of this experience would be directly applicable to monitoring a comprehensive nuclear disarmament regime, although the standards for verification would have to be considerably higher than they are at present, for two reasons. First, the former nuclear-weapon states would have considerable experience in producing nuclear weapons and their components, and presumably would find it much easier to circumvent current safeguards without detection than states that had never produced nuclear weapons. Second, the nuclear-weapon states are likely to require that barriers to the acquisition of nuclear weapons by current non-weapon states be increased as one condition for agreeing to dismantle their own arsenals.

Under the NPT, non-nuclear-weapon states promise “not to manufacture or otherwise acquire nuclear weapons or other nuclear explosive devices.” The Treaty acknowledges the right of these states, in forgoing nuclear weapons, to enjoy the peaceful uses of nuclear energy. To prevent the “diversion of nuclear energy from peaceful uses to nuclear weapons,” the non-nuclear-weapon states agree to accept IAEA safeguards on all their nuclear activities. In addition, all parties agree not to transfer nuclear materials or equipment to any other state unless those materials or equipment are subject to IAEA safeguards.

IAEA safeguards are designed to detect diversions of significant quantities of nuclear material with high confidence, and to provide warning of such diversions in a timely manner.[40] The safeguards are based on audits of each country’s internal records of nuclear-material inventories and changes in those inventories at each facility, and on the collection of data to verify the accuracy of those records. IAEA inspectors count items such as fuel rods, estimate amounts of nuclear material, affix seals to indicate whether items have been moved or tampered with, and install video cameras and radiation detectors to monitor the movement of nuclear materials. Inspectors also verify the design of facilities to understand their capacity and the flow of nuclear materials within them, and to evaluate the operator’s measurement systems. The frequency of inspections depends on the quantity and quality

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[39] The following discussion is restricted to providing timely warning of an attempt to produce nuclear weapons by countries that had disarmed or had never possessed nuclear weapons. The possibility that countries might not disarm completely or might not put all their fissile materials under safeguards was discussed above. If hidden nuclear devices exist, it would be impossible to provide “timely warning” of their deployment. If hidden fissile materials exist, it would be extremely difficult to provide timely warning of the construction of nuclear weapons, depending on what other materials, components, equipment, and facilities had been hidden as well.

[40] The IAEA defines “high confidence” as a 90-percent probability of detecting the diversion of a significant quantity of nuclear material. A “significant quantity” is defined as 8 kilograms of plutonium or 25 kilograms of U^{235} in the form of HEU, which represents the amount thought to be needed for a state to make its first nuclear explosive, taking into account processing losses. “Timely warning” is based on the estimated time it would take for a state to convert the diverted material into a finished weapon component; for unirradiated plutonium or HEU, the IAEA goal is to detect diversions within one month; for irradiated plutonium or HEU (e.g., spent fuel), three months; for natural or low-enriched uranium, one year. See OTA, *Nuclear Safeguards*, 45, 57.

of nuclear material present. Facilities containing spent reactor fuel, for example, are inspected less frequently than those with separated HEU or plutonium, but more frequently than facilities containing only natural or low-enriched uranium (LEU).

Improving IAEA Safeguards

Revelations in the wake of the Gulf War that Iraq had pursued an extensive nuclear weapon program while a member of the NPT focused international attention on the shortcomings of IAEA safeguards. Among these are the weak authority of the Agency to conduct inspections on short notice and at undeclared facilities, the inability of the IAEA to focus inspection effort on states of proliferation concern, the focus only on nuclear materials to the exclusion of other weapon-development activities, the right of states to refuse certain inspectors or inspectors from certain states, and the shortage of funding to achieve existing inspection goals.[41]

At a minimum, these defects in IAEA safeguards would have to be corrected before the safeguards could be used as a basis for monitoring a comprehensive disarmament agreement. The single most important factor in the failure of safeguards in Iraq was the inability to detect undeclared facilities. In principle, a country could attempt to violate a disarmament agreement either by diverting fissile materials from declared facilities or by building secret facilities to produce unsafeguarded material. IAEA inspections focus on the diversion scenarios, and have been very effective in deterring the diversion of significant amounts of material from declared, safeguarded facilities.[42] It is precisely for this reason that countries have been, and would continue to be, more likely to cheat by constructing clandestine nuclear facilities.

If discovered, the mere existence of an undeclared nuclear facility would be prima facie evidence of a violation sufficient to prompt the international community to take action. The challenge is to detect undeclared facilities in the first place. With a reasonably high probability, the verification system must provide clear and convincing evidence of an undeclared facility, if one exists. Just as important, it must provide adequate reassurance when no such facilities exist.

At least four major changes in the current safeguards regime are required to deal with the possibility of undeclared facilities. First, intelligence information of the highest quality, particularly high-resolution imagery and signals intelligence that might reveal the construction and operation of clandestine nuclear facilities, must be incorporated in the verification process. Today, this information is available only through national intelligence. The quality of commercial imagery will continue to improve in the coming decades, but it is unlikely that any commercial service will approach the overall intelligence capabilities of the United States. Before the Gulf War, governments did not share

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[41] This section draws heavily on chapter 3 of OTA, *Nuclear Safeguards*.

[42] There have been no known diversions of significant amounts of safeguarded material, and no reason to believe that such diversions have occurred without detection. Iraq and Romania used safeguarded research reactors to produce gram quantities of plutonium. North Korea and Pakistan also may have diverted small amounts of material from safeguarded facilities, but in neither case were full IAEA safeguards applied.

information about the Iraqi nuclear program, if they had any, with the IAEA. The United States and other countries subsequently have been more forthcoming in sharing intelligence information with the IAEA, and US satellite photographs were vital in mobilizing international support for IAEA efforts to uncover undeclared nuclear activities in Iraq and North Korea. Such informal, ad-hoc, and one-sided mechanisms are unlikely to be adequate under a general disarmament agreement, however.

There is no entirely satisfactory solution to the intelligence problem. As long as the best intelligence information is in the hands of a few countries, observers will expect that these countries will use this information for their own purposes. The fact that intelligence assets are concentrated in the hands of the current nuclear-weapon states may be particularly troubling. Although some might hope that these countries would keep an eye on each other, others might fear that they would collude to keep secret the existence of certain facilities. If, on the other hand, high-quality intelligence information became more widely available, or available directly to the United Nations, it is more likely that countries that wished to cheat would learn how to hide their nuclear activities.

Second, extensive environmental monitoring would improve substantially the ability to detect undeclared facilities, by detecting the distinctive radioactive or chemical substances emitted during their operation.[43] Environmental sampling would be especially effective in detecting plutonium separation, since large amounts of radioactive gases are released into the environment when the spent fuel is dissolved. These gases can be trapped with considerable difficulty and expense, but releases cannot be eliminated entirely. Uranium enrichment is much harder to detect because emissions are low and uranium exists in nature; depending on the enrichment process used, enriched uranium might be detected only a few kilometers or less downwind. High concentrations or unusual chemical forms of uranium in the air or water, however, could indicate the presence of undeclared uranium mining, purification, or conversion operations.

The operation of most existing civilian and military nuclear facilities can be detected rather easily because of their large size and because special precautions usually have not been taken to minimize or hide emissions beyond measures required to protect public health and safety. Nuclear reactors, for example, typically are built above ground on the shores of a large body of water, and are recognized easily by their distinctive appearance and the discharge of large quantities of heat. Releases of radioactive gases from existing reprocessing plants can be detected thousands of kilometers downwind, and particles of enriched uranium from commercial enrichment plants can be detected at distances of tens of kilometers. An enrichment, reactor, or reprocessing facility sized to produce only a few bombs-worth of material each year, however, would be more difficult to detect, especially if precautions were taken to disguise the facility and to minimize emissions. In those cases, detection would rely primarily on the possibility of accidents. That may be a larger possibility than

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[43] Office of Technology Assessment, *Environmental Monitoring for Nuclear Safeguards*, OTA-BP-ISS-168 (Washington, DC: U.S. Government Printing Office, 1995).

it seems, given that even minor accidents can lead to detectable releases, and that some of the precautions taken to minimize routine emissions, such as storing volatile and reactive wastes, can increase the probability of accidents.

Third, the chance of detecting clandestine nuclear facilities could be increased by expanding the scope of safeguards to include uranium mining and milling operations. Currently, safeguards begin when uranium is converted into a chemical form suitable for fuel fabrication or uranium enrichment; inventories of refined natural uranium ("yellowcake") are neither reported nor safeguarded. A clandestine effort to produce plutonium or HEU would require substantial quantities of uranium—5 to 10 tons of yellowcake per significant quantity.[44] A program to produce enough material for five weapons per year would require 25 to 50 tons of yellowcake per year, which is a detectable mining and milling operation.[45] Extending safeguards to yellowcake and uranium ore would make it difficult to divert uranium from safeguarded mines and mills to clandestine fuel-fabrication or uranium-enrichment facilities, and it would make undeclared mining and milling vulnerable to detection. Inspectors could visit a random sample of mines in areas where geological surveys indicated that uranium ores were present in order to verify the absence of undeclared uranium mining and milling.

Fourth, the IAEA's authority to inspect undeclared sites on short notice could be improved dramatically. Current safeguards agreements include provisions for "special" inspections at undeclared sites, but these inspections must be carried out "in consultation" with the state. In practice the IAEA must notify the state in advance, provide reasonable justification for the inspection, and obtain the state's permission. Combined with the fact that a special inspection has been requested only once in the history of the IAEA (in the case of North Korea), the requirement for advanced notification and consultation severely weakens the IAEA's ability to deter or confirm the construction and operation of clandestine facilities.

Special inspections can be compared to the "challenge" inspections provided for in the 1993 Chemical Weapons Convention (CWC). Any CWC party can request a challenge inspection of any location or facility within the territory of any other party. The state being challenged has no legal right to refuse the inspection; under the terms of the Convention, it must provide prompt access to the site

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[44] Producing 1 kilogram of HEU (90 percent U^{235}) requires 180 to 420 kilograms of natural uranium feed, depending on the tails assay (0.2- to 0.5-percent U^{235}), or 4.4 to 10.6 tons of uranium per significant quantity of HEU (25 kilograms). Producing 1 kilogram of weapon-grade plutonium (6-percent Pu^{240}) requires about 1000 kilograms of natural uranium, assuming a burnup of 1.2 GWd/te(U) and 0.9 kg(Pu)/GWd 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). Yellowcake (U_3O_8) is 85 percent uranium.

[45] Current world production of yellowcake is about 90,000 tons per year. The United States, Russia, China, and France each produce about 2,000 tons per year. Only two countries (Canada and Australia) produce substantially more than this; most countries produce much less. A mining and milling operation that yielded 25 to 50 tons per year would represent at least one percent, and often more than ten percent, of a country's total production.

in question.[46] Access to the site can be "managed" by the challenged party, however, to protect proprietary or national-security information; papers can be removed, equipment shrouded, or access can be restricted to randomly selected rooms.[47] This level of access should be more than sufficient to verify compliance with a nuclear disarmament agreement, since ultra-sensitive environmental sampling techniques could detect the distinctive isotopic or chemical signatures of nuclear facilities even if attempts had been made to clean facilities, trap emissions, or move equipment.

The preceding discussion has focused on the possibility of detecting undeclared facilities for the production of plutonium or HEU. Some have criticized the IAEA's exclusive focus on safeguarding nuclear materials, reasoning that the NPT's prohibition on the "manufacture" of nuclear explosives applies to the entire research, development, and production process.[48] Although monitoring authorities certainly should be alert for other signs of weapon development, they should not put much hope in the possibility of detecting the research, development, and manufacture of nuclear weapons, simply because these activities are so easily hidden from spy satellites and on-site inspectors. The United States, with its massive intelligence-gathering apparatus, was unable to identify specific sites of such activities in Iraq, South Africa, or North Korea, but it had much more success in identifying fissile-material production. Imports of certain types of equipment might indicate the existence of a weapon-development program, but they would be less likely to identify a specific facility or provide the sort of conclusive evidence that would trigger international sanctions. Weapon-development activities probably would be revealed only through sloppiness or leaks of information. High-explosive assemblies might be tested in isolated, distinctive facilities, for example, or a disaffected employee might reveal the location of key facilities. Such discoveries likely would be serendipitous, however, and it is difficult to outline a systematic program for ferreting out such information, aside from general intelligence collection.

One possibility would be to expand the scope of safeguards to materials other than plutonium and HEU that are uniquely useful in nuclear weapons, such as tritium and enriched lithium. In the absence of nuclear weapons, tritium and enriched lithium would be used mostly in nuclear fusion and other scientific research, and therefore might be subjected to safeguards without too much trouble. Other important materials (e.g., beryllium and high explosives) and subcomponents (e.g., neutron generators and high-speed switches) are used in such a wide variety of industrial applications that safeguards of the type now applied to nuclear materials would be impractical and ineffective. Export controls are applied already to most such items by the Nuclear Suppliers Group, but these controls

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[46] Requests can be rejected by the CWC's Executive Council, however, if they are deemed frivolous, abusive, or beyond the scope of the Treaty.

[47] Although managed access falls short of "anytime, anywhere" inspections, the burden of proof remains on the inspected party to demonstrate that illegal activities are not occurring at the facility in question. The inspectors would have to be convinced, for example, that shrouds did not cover illegal equipment. Random access is used to limit the impact of the inspection on the normal operation of the facility, and could not be manipulated to deny access to areas housing illegal activities.

[48] Leonard S. Spector, "Repentant Nuclear Proliferators," *Foreign Policy*, no. 88 (Fall 1992): 30–31.

have been circumvented many times in the past. Export controls could be strengthened as part of a disarmament agreement, but this mechanism has inherent weaknesses that limit its reliability.

Although the existing verification regime appears to have been highly successful in deterring the diversion of significant amounts of materials from safeguarded facilities, it is important to improve the effectiveness and efficiency of safeguards as the number and size of nuclear facilities grow. Of particular concern are facilities that handle large quantities of weapon-usable material in bulk form: reprocessing, enrichment, and mixed-oxide fuel-fabrication facilities. As the size of these facilities grows and as older facilities in the nuclear-weapon states are placed under safeguards, measurement errors could grow so large that detecting significant diversions of material might be problematic with current techniques. In addition, the current standard for “significant quantity” would have to be revised downward as the current nuclear-weapon states came under safeguards, since these countries know how to build nuclear weapons with far less than the 8 kilograms of plutonium or 25 kilograms of HEU that the IAEA judges necessary for a state to make its first nuclear explosive.[49] The standard for “timely detection” also would need to be revised from one month to perhaps one week or less, since the current nuclear-weapon states presumably could convert diverted material into a fabricated weapon component in a matter of days.

Meeting even the current safeguards standards at large reprocessing plants would strain the limits of safeguards technology, and it may not be possible to meet the more stringent standards suggested here with a reasonable level of monitoring effort. Meeting current standards would require moving to near-real-time accountancy, in which sensors accurately and automatically measure and track the movements of nuclear material within the plant. Facility operators also would have to impose fewer restrictions on the access of inspectors to the plant and demonstrate less concern about the release of proprietary information. Unless inspectors know as much about a plant and its operation as the facility operators themselves, it probably will be impossible to obtain an adequate level of assurance of non-diversion. Indeed, it may simplify safeguards greatly if facility operators simply would share all their data, in real time, with the inspecting agency, which would analyze it for possible inconsistencies or indications of diversion.

Expanding safeguards horizontally to the current weapon states, and vertically to include yellowcake and tritium, and tightening standards for detecting diversions would require at least a tripling of the current IAEA safeguards budget (currently about $80 million), but the costs would not be large compared with those of other arms control agreements such as START and the CWC. In some cases, it may be possible to improve timeliness criteria while reducing inspection costs. For example, using satellite uplinks to relay information from various sensors placed inside nuclear facilities directly

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[49] The amount of material in nuclear weapons is secret, but the US Department of Energy recently stated that “Hypothetically, a mass of 4 kilograms of plutonium . . . is sufficient for one nuclear explosive device.” (Classification Bulletin WNP-86, 8 February 1994; quoted in OTA, *Nuclear Safeguards*, 67.) Nuclear explosives can be built with even less; press reports of the destruction of a Russian nuclear device buried at the Semipalatinsk test site in Kazakstan stated that the device contained about 1 kilogram of plutonium and would have yielded 1 kiloton.

to IAEA headquarters would provide real-time assurance that materials had not been diverted, while reducing travel costs and increasing the productivity of inspectors.

Transforming the NPT and the IAEA

The preceding discussion of safeguards has taken place within the constraints of the NPT and the IAEA charter. The NPT does not provide an adequate basis for complete disarmament. It is likely that a disarmament agreement would replace the NPT and other existing nuclear arms control treaties. This new agreement would present an opportunity to completely revamp the safeguards regime to include not only the incremental measures noted above, but more far-reaching measures that could alter fundamentally the nature and structure of the nuclear industry and the authority of the IAEA or its successor agency.

A disarmament treaty should close two loopholes in the NPT. Although the NPT prohibits non-nuclear-weapon states from developing nuclear explosives and requires safeguards on all peaceful uses of nuclear energy, it allows states to withdraw material from safeguards for non-explosive military uses—that is, for naval nuclear reactors. No state has exercised this right, although several have considered the possibility over the years. Although withdrawn material eventually would be returned to safeguards, this would occur twenty or more years after the material had been withdrawn. US and UK naval reactors, and some French and Russian reactors, each contain more than a hundred kilograms of HEU, which would represent an unacceptable breech of material accountability in a disarmed world.[50] A disarmament agreement should require that all nuclear materials, regardless of their use, be subject to safeguards that meet appropriate timeliness criteria. This would require that inspectors be given access to naval fuel-fabrication, fuel-storage, and reprocessing facilities; that inspectors be present during the assembly and loading of new reactor cores; and that periodic inspections of operating naval reactors be carried out to verify that irradiated fuel had not been diverted.[51]

A second loophole in the NPT is Article V, which allows for "peaceful" nuclear explosions (PNEs). Although the Treaty prohibits non-nuclear-weapon states from developing nuclear explosives of any kind, it guarantees access to nuclear devices for peaceful uses, presumably provided by one of the nuclear-weapon states. No state has ever requested a PNE, and the United States and Russia no longer have active PNE programs. There is no essential difference between a "peaceful" device and a weapon, and the Comprehensive Test Ban Treaty (CTBT) will ban all nuclear explosions, including

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[50] D.D. Lanning and T. Ippolito (quoted in Marvin M. Miller, "Nuclear Submarines and their Implications for Weapons Proliferation," in *Averting a Latin American Nuclear Arms Race,* ed. Paul L. Leventhal and Sharon Tanzer [Washington, DC: MacMillan, 1992], 153–164) give three core designs for a 50-MWt naval reactor: two with 20-year lifetimes (110 kg of 97.3-percent-enriched; 1000 kg of 20-percent-enriched uranium) and one with a 10-year lifetime (1100 kg of 7-percent-enriched uranium).

[51] Under current timeliness standards, inspections of operating reactors every three (HEU) or twelve (LEU) months would be sufficient.

PNEs.[52] Some scientists continue to believe that PNEs will prove to be of great benefit someday, and perhaps even be essential for the survival of humanity if the Earth was threatened by asteroid impact. It would seem unwise, however, to maintain a ready stockpile of nuclear weapons—much less an active program to design and build such devices—to guard against such an unlikely possibility. If, in the future, a situation arose in which the use of nuclear explosives would seem to be of great benefit to humanity, national decision makers would be in a better position to make decisions about how to produce and maintain such devices, based on the nature of the world order and the circumstances that require the use of nuclear weapons.

Nuclear Energy in a Disarmed World

A central issue is how nuclear power and other peaceful nuclear activities could be structured and managed in a disarmed world. The first nuclear disarmament proposal, the Baruch Plan, envisioned the creation of an "International Atomic Development Authority" that would manage or own all "potentially dangerous" nuclear activities, inspect and license all other nuclear activities, and be at the forefront of all nuclear research and development. The Authority would control directly all mining, refining, and distribution of uranium, as well as all facilities capable of producing fissile materials.[53]

An agency with the scope and authority envisioned by the Baruch Plan would be impractical today. When the Baruch Plan was presented by the United States to the United Nations in 1946, nuclear power was a distant dream; today more than 430 nuclear reactors in over 30 countries account for nearly 20 percent of global electricity production. Also, at the time of the Baruch Plan, scientists believed that nuclear fuels could be "denatured" or made unusable for weapons; the denatured fuels then would be leased to countries or utilities for use in national facilities. We now know that *all* nuclear fuel cycles must involve fuels (fresh or spent) that contain weapon-usable materials that can be obtained through a relatively straightforward chemical separation process.[54] Still, it is wise to ask whether aspects of the nuclear fuel cycle that are especially worrisome should be limited or brought under international control.

One of the most severe shortcomings of the current regime is that non-nuclear-weapon states are permitted to own and operate facilities capable of producing plutonium and HEU in forms that are

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[52] Article VIII (Review of the Treaty) of the CTBT leaves open the possibility of reconsidering the issue of PNEs in the future. The Treaty would need to be amended, however, to permit PNEs.

[53] U.S. Department of State, *Documents on Disarmament, 1945–1956* (Washington, DC: U.S. Government Printing Office, 1960), 10–15.

[54] The fissile isotopes U^{235} and U^{233} can be denatured by diluting them with the non-fissile isotope U^{238}. Isotope separation, which is far more difficult than chemical separation, would then be necessary to produce weapon-usable HEU. It was hoped initially that the fissile isotope Pu^{239} could be denatured by adding Pu^{240}, but, unlike U^{238}, Pu^{240} has a finite critical mass. Since Pu^{239} is produced from U^{238}, any fuel containing significant amounts of U^{238} will produce plutonium, which can be chemically separated. U^{233} is produced from natural thorium, but unless the U^{233} is diluted with U^{238} (which would lead to the production of plutonium), the fresh fuel would be weapon-usable HEU. See "Report to the American Physical Society by the Study Group on Nuclear Fuel Cycles and Waste Management," *Reviews of Modern Physics* 50, no. 1, part II (January 1978): S29, S95.

directly usable in nuclear weapons, and can produce, stockpile, and use these materials so long as they are subject to safeguards. For example, states can enrich uranium, separate plutonium from spent reactor fuel, use plutonium and HEU reactor fuels, and stockpile fresh HEU and separated plutonium. Some of these activities are very difficult to safeguard and pose risks of undetected diversion, and all of them pose the risk of rapid break-out from the disarmament regime.

Some analysts believe that the risks associated with civilian uses of HEU and plutonium are so great that commerce in these materials should be discouraged or even outlawed. The United States has been the leading proponent of this view, having decided in the late 1970s to discourage the civilian use of HEU and plutonium world-wide. As a result, the United States adopted the "once-through" fuel cycle, in which plutonium-bearing spent fuel is treated as waste, and launched a program to develop LEU fuels for HEU-fueled research reactors. The United States reaffirmed its opposition to the use of plutonium fuels in 1993, although it promised not to interfere with the plans of allies with comprehensive non-proliferation commitments and established civilian reprocessing or plutonium facilities.

Few countries share the US view of the dangers of the civilian use of plutonium. Indeed, this policy has been a major point of contention between the United States and three of its closest allies, France, Japan, and the United Kingdom, which have major programs for the separation and use of plutonium. These programs were developed in the 1970s, when demand for nuclear power was projected to grow rapidly and uranium was thought to be relatively scarce. Increased supply and decreased demand has pushed uranium prices to record lows, however, making plutonium uneconomical as a reactor fuel for the foreseeable future. Belgium and Germany have abandoned their domestic reprocessing programs, but several countries, including Russia and India, cling to ambitious plans to expand the use of plutonium fuels in spite of the now obvious economic disadvantages of doing so.

Such policies, of course, are subject to change over the time scale in which nuclear weapons might be eliminated. In the long term, plutonium use is tied to the future of nuclear power and uranium extraction. If nuclear power does not expand much beyond the current level, then the price of uranium should remain low and we might avoid building a new generation of reprocessing facilities twenty or thirty years from now. If, on the other hand, the demand for nuclear power grows, then the price of uranium will increase. This might make the use of plutonium fuels economically attractive, triggering a huge expansion in the separation, handling, and transport of plutonium.[55]

If the civilian use of plutonium or HEU continued over the longer term, additional technical and institutional barriers could be introduced to increase the probability of detecting diversions, as well as to raise the amount of warning time available. Fissile materials could be placed in forms that would not be directly usable for weapons. A good example is spent reactor fuel: the intense

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[55] Alternatively, it might be cheaper to extract uranium from sea water. Although present at low concentrations, the amount of uranium contained in sea water is huge, and economical extraction would make plutonium use unnecessary.

radioactivity protects it from theft; diversion of spent fuel would be detected easily and quickly; and reprocessing would be necessary to recover the plutonium for use in a weapon. Similar benefits might be obtained by altering commercial reprocessing and fuel-fabrication processes so that plutonium would not be present in weapon-usable forms. Schemes that have been suggested include mixing or precipitating uranium with plutonium and adding neutron emitters.[56] These would be significant barriers for subnational groups, but not for most nations that host nuclear industries. Adding highly radioactive materials to the fuel, moreover, would add significantly to the costs and hazards of fabricating and handling reactor fuel.[57]

The risks of diversion of weapon-usable materials also could be reduced by internationalizing certain parts of the nuclear fuel cycle. As noted above, traditional IAEA-type safeguards may be unable to detect the diversion of significant quantities of weapon-usable materials in a timely manner from large facilities that handle these materials in bulk form, such as reprocessing, enrichment, and fuel-fabrication plants. If such activities were managed directly by the IAEA or, as envisioned in the Baruch Plan, an "International Atomic Development Authority," it would be easier to deter or detect diversions by states. Similar arrangements could be extended to the storage and use of fresh plutonium and HEU fuels, or even spent fuels containing plutonium or HEU. National reactors might be permitted to burn only LEU fuels, with the spent fuel turned over to international reprocessing or storage centers; reactors burning plutonium or HEU fuels would be managed by an international authority.

Some analysts believe that the continued use of nuclear energy is incompatible with the goal of a disarmed world. As noted above, all fuel cycles involve weapon-usable materials; therefore, the use of nuclear energy carries with it the ever-present danger that the host nation would decide to use these materials to build nuclear weapons. The existence of a civilian nuclear industry also maintains technical expertise that could be applied to a weapon program, and provides a background of legal activity against which it would be more difficult to detect an illegal program. Internationalizing certain aspects of the fuel cycle could help deter and detect decisions to go nuclear, but could not prevent civilian nuclear facilities and materials from being redirected to weapon uses. In this view, Article IV of the NPT, in which non-nuclear-weapon states are guaranteed the right "to develop research,

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[56] Adding large amounts of uranium (e.g., 20 kilograms of uranium per kilogram of plutonium) would require a substantial glove box facility to do the chemical separations necessary to recover the plutonium. If such a facility was available, however, the process could be completed in a few days. Even an advanced nation might have problems removing trace quantities of potent neutron emitters, such as californium 252, from plutonium, but this barrier could be overcome through weapon design.

[57] The IAEA considers materials emitting more than 100 rads per hour at a distance of one meter to be sufficiently self-protecting so as to require a lower level of safeguarding. The comparable dose rate from typical spent fuel assembly is 20,000 rads/hr after one year, 2,000 rads/hr after 15 years, and 200 rads/hr after 100 years (mostly from cesium–137). (Committee on International Security and Arms Control, National Academy of Sciences, *Management and Disposition of Excess Weapons Plutonium* [Washington, DC: National Academy Press, 1994], 151.) Thus, plutonium fuels might be considered self-protecting if they contained about the same concentration of cesium 137 as spent fuel.

production and use of nuclear energy" and "the fullest possible exchange of equipment, materials and scientific and technological information for the peaceful uses of nuclear energy," is fundamentally flawed.

This view is unlikely to become widespread, at least while nuclear power is viewed as an important energy source. Global energy use continues to grow at several percent per year, and many countries do not have abundant energy resources. The prospect of global climate change has redoubled efforts to replace fossil fuels, and nuclear power is one of the few non-fossil energy sources that can be expanded substantially at prices comparable to current market prices. As a result, it would be difficult to convince policymakers in many countries that nuclear energy is incompatible with disarmament; if forced to choose between them, some might value the benefits of nuclear energy more than those of disarmament. There are, moreover, important precedents in the Biological Weapons Convention and the Chemical Weapons Convention, which, in banning biological and chemical weapons, did not infringe on the right of states to use biological and chemical agents for peaceful purposes.[58]

That said, an undeniable flaw in the current regime is that the charter of the International Atomic Energy Agency requires that it both *promote* and *safeguard* the peaceful uses of nuclear energy.[59] The tension in this relationship is evident in the battle over the IAEA budget, in which some member states insist that any increase in the safeguards budget should be matched by a comparable increase in the technical assistance budget. A disarmament agreement should relieve this tension either by creating a new inspection agency similar to the Organization for the Prohibition of Chemical Weapons, the sole mission of which is to verify and facilitate compliance with the CWC, or by altering the IAEA's charter to eliminate its technical assistance function.

Social Verification

So far we have discussed what might be called "technological" means of verifying compliance with a disarmament agreement: the monitoring and management of nuclear facilities, safeguarding of nuclear materials, environmental sampling, performing challenge inspections, and so on. Although such measures are powerful, they are not foolproof. Under virtually any verification regime, it would be technically possible with careful planning, and barring a major accident, to build a small nuclear arsenal while avoiding detection by the international inspection or national intelligence agencies. In

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[58] According to Article X of the Biological Weapons Convention, states parties "undertake to facilitate, and have the right to participate in, the fullest possible exchange of equipment, materials and scientific and technological information for the use of biological agents and toxins for peaceful purposes."

Similarly, under Article VI of the Chemical Weapons Convention, each state "has the right . . . to develop, produce, otherwise acquire, retain, transfer and use toxic chemicals and their precursors for purposes not prohibited by this Convention. . . . The provisions of this article shall be implemented in a manner which avoids hampering the . . . international exchange of scientific and technical information and chemicals and equipment for the production, processing or use of chemicals for purposes not prohibited under this Convention."

[59] For an alternative view, see James Leonard, Martin Kaplan, and Benjamin Sanders, "Verification and Enforcement in a NWFW," in *A Nuclear-weapon-free World: Desirable? Feasible?* 133–134.

that event, detection and timely warning of rearmament would rely solely on "leaks" or "whistle-blowing" by those with knowledge of the program.

A disarmament regime should be designed to increase the probability of whistle-blowing. In contrast with the problem of maintaining a small number of existing weapons, a program to produce or divert nuclear materials and build nuclear weapons would involve several hundred scientists and technicians with a wide range of skills, multiplying greatly the probability of a leak. The disarmament treaty could require parties to enact laws obligating citizens to report any information about possible violation of the treaty to the international inspection agency, and making it illegal for states to retaliate against whistle-blowers.[60]

Social means of verification may prove in the end to be the most reliable and robust source of reassurance that states are not rearming, at least for states that are reasonably open and democratic. For authoritarian regimes such as Iraq and North Korea, however, where citizens are routinely punished for even minor disagreements with their governments, whistle-blowing would be far less reliable. Defections by knowledgeable people can and do happen (important information on the Israeli and Iraqi nuclear programs was supplied by whistle-blowers), but they would be serendipitous and cannot be counted on.

Other transparency measures would be easier to arrange on a government-to-government basis. For example, states could publish detailed budgets for all government-sponsored research, and could provide access to all government-funded laboratories. Such steps could help to allay concerns that weapon-development work was continuing. Although governments would want to retain some degree of secrecy to protect classified or proprietary information, it often would be possible to demonstrate that secret activities were not related to nuclear weapon research or development. In addition, governments could agree to exchange lists of scientists, engineers, and technicians with skills that were especially relevant to the production of nuclear materials and nuclear weapons.

It has been suggested that the advance of surveillance and communications technologies may make it much easier to track the actions of citizens. Certain US communities, for example, are installing video cameras and acoustic detectors on street corners to monitor crime, and voice recognition software will make it possible to automatically monitor the telephone conversations of large numbers of people. Although such technologies, if implemented, could prove useful in monitoring the actions of sub-state actors, it is highly unlikely that they could be used to monitor or constrain the actions of governments. Short of a revolution in international politics, governments would not provide detailed information on the internal activities of their citizens to international authorities. And even if such information was provided, governments would know how to circumvent the monitoring system, which they would control.

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[60] Joseph Rotblat, "Societal Verification," 103–118.

Break-out

The preceding analysis has dealt mainly with various forms of clandestine cheating: hidden stockpiles of bombs or pits, surreptitious diversion of fissile materials from safeguarded facilities, or the production of fissile materials and bombs in secret facilities. The detection of clandestine cheating is the natural focus of the verification endeavor; after all, no special effort is needed to detect or provide warning of the open abrogation and violation of an agreement.

We can gain some useful insights, however, by considering break-out scenarios. For example, the time required to break out of a disarmament agreement would set a benchmark for the warning time that the verification system must give of a clandestine violation, and for the time that would be available for a political or military response to evidence of a violation.

How quickly could a country build nuclear weapons after a decision was made to break out of a disarmament agreement? Based on the experience of Iraq and North Korea, it would take five or more years for a developing country with little or no existing nuclear infrastructure to produce fissile materials and fabricate a workable bomb. Industrialized countries could build a bomb much more quickly, however.[61] Consider the Manhattan Project: beginning with no nuclear infrastructure of any kind, and with only a rudimentary knowledge of basic nuclear science and technology, the United States succeeded in building two very different kinds of nuclear weapons in less than three years. Almost all industrialized countries, in a national emergency, could accomplish the feat in much less time today, assuming that they had access to modest stocks of natural uranium.

The time required by an industrialized country to build nuclear weapons would depend mostly on whether existing civilian nuclear facilities and materials could be used for the weapon program. If a country had no nuclear facilities, it might take one to two years to build and operate a small reactor and reprocessing facility or an enrichment facility and thereby produce a few bombs-worth of material.[62] If an existing power or large research reactor was available, it might take six to twelve months to build and operate a reprocessing facility to recover plutonium from existing stocks of spent fuel or from a batch of newly irradiated fuel. If a reprocessing or enrichment facility was available, the time needed to produce large quantities of fissile materials would be reduced to one or two months. If stockpiles of HEU or separated plutonium existed, they would be available for immediate diversion to a weapon program. The design and fabrication of the bomb itself might take as little as one month for a former nuclear-weapon state, or as much as a year for other industrialized countries, and most of this work could take place during the acquisition of the fissile materials.

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[61] There is no precise definition of "industrialized countries." Today, about thirty countries have the sort of industrial infrastructure and scientific talent that could support the successful construction and operation of nuclear facilities and nuclear weapons on a crash basis. A list would include all of the declared, de-facto, and former nuclear-weapon states, all or most of the OECD states, and many of the newly industrialized countries (e.g., Brazil, Argentina, South Korea, and Taiwan).

[62] In the case of plutonium production, it might take 6–18 months to build the reactor and the reprocessing facility, 1–3 months to irradiate the first batch of fuel, about 3 months to cool the fuel, and 1–3 months to separate the plutonium. The separated plutonium could be fabricated into pits within a week or two. As noted below, the design, fabrication, and assembly of other bomb components could take place during the production of the plutonium.

Thus, the international community must stand ready to respond very quickly to indications of cheating or break-out. This is particularly true for former nuclear-weapon states and industrialized countries that maintain stockpiles of fissile materials, and which could produce weapons in as little as a few months. As noted above, a response could include economic sanctions designed to cripple an offender's economy, military action designed to destroy the nuclear program or remove the government responsible for initiating it, the readying of conventional forces (or, if they exist, international nuclear forces) to deter or respond to the use of nuclear weapons, or the rebuilding of national nuclear arsenals for the same purpose.

The possibility of rapid break-out could have both positive and negative effects on the operation of the verification system. On the one hand, the industrialized countries might not worry excessively about the possibility of cheating, because they would be confident in their ability to assemble a nuclear arsenal quickly in an emergency. For this reason, these countries would not be viewed as having strong incentives to violate the agreement clandestinely, and the international community might be satisfied with the reassurance provided by the verification system that such countries were not cheating. On the other hand, countries that intend to violate a disarmament agreement might do so secretly at first, in order to obtain the largest advantage possible, with plans to openly break out if the clandestine program was detected. This possibility could put pressure on the verification system to detect cheating at the earliest possible moment. Dangerous instabilities could result, in which countries, fearing that some other country was cheating and preparing to break out of the agreement, would respond hastily and disproportionately to evidence of cheating—evidence that ultimately might prove to be erroneous. A disarmament regime would have to be structured to avoid such instabilities by allowing the inspection agency time to investigate fully any evidence of cheating without triggering a premature response.

Conclusions

This paper has outlined the technological possibilities for verifying compliance with a nuclear disarmament treaty. Many of these possibilities do not depend on dramatic improvements in world politics, and could be implemented soon. In particular, it is important for the nuclear-weapon states to declare in detail their stockpiles of nuclear devices and fissile materials and to allow these declarations to be verified. Unless the nuclear-weapon states begin this process today, when stockpiles are huge and shrouded in secrecy, they will fail to lay the necessary foundation for nuclear disarmament, because today's uncertainties will be magnified greatly as we move from tens of thousands to hundreds of warheads and ultimately to zero.

In the final analysis, however, no conceivable verification regime could provide absolute assurance that former nuclear-weapon states had not hidden a dozen or even a hundred "bombs in the basement" (or enough plutonium or HEU to build such a stockpile), no matter how cooperative and transparent the parties had agreed to be. In other words, even the most intrusive inspection regime could not detect a small stockpile of carefully hidden bombs or plutonium with high confidence. And although improved and expanded IAEA safeguards, together with internationalization of certain aspects of the civilian nuclear fuel cycle, would give states reasonably high confidence that parties were not clandestinely producing fissile materials for nuclear weapons, any state with a substantial nuclear industry would be technically capable of producing or diverting fissile materials and building nuclear weapons in less than a year, and perhaps in as little as a few months.

We therefore are driven to the conclusion that nuclear disarmament would be possible only in a world in which such scenarios were generally regarded as highly unlikely or unimportant. For example, if relations between all the nuclear powers were as congenial as are today's relations between the United States, the United Kingdom, and France, then we would not worry about the possibility of "bombs in the basement" or rapid break-out. If, moreover, the decision-making processes of these and other key governments were as transparent as those of the US government, then states might judge that the probability of hiding bombs or plutonium from inspectors for many years was negligible. Achieving and maintaining such good relations and transparency probably would require having stable democratic governments in place in Russia and China, which would itself increase the prospects for self-enforcement of international obligations.

It may seem as if verification thus has been reduced to a trivial task: in order for disarmament to be possible, states would have to possess a degree of mutual trust and transparency that would make verification (and disarmament itself) a mere formality. This formulation is too simplistic, however, because the disarmament process is iterative. Parties agree to reductions on the assumption of shared goals; the verification of these reductions builds confidence between the parties in that assumption, making increased transparency and deeper reductions possible. The START negotiations made dramatic progress only after relations between the United States and the Soviet Union improved, but START I would not have been signed or ratified without the extensive verification provisions it contained. The successful implementation of the INF Treaty a few years earlier also was important in creating the environment that made improved relations and the START treaties possible. Indeed, dramatically improved relations between Russia, China, and the other nuclear-weapon states may be possible only in an environment in which they are engaged in a process of mutual and progressive restraints on their nuclear arsenals, since those arsenals are potent symbols of continuing mistrust.

The cheating scenarios outlined above also would become unlikely or unimportant if adequate precautions had been taken to deal with the possibility of small-scale cheating or rapid break-out. If, for example, the nuclear-weapon states and other great powers had pledged to defend each other against aggressors, or to act together to punish nations that violated the nuclear disarmament agreement, then this would decrease the benefits and increase the costs of cheating substantially (assuming, of course, that such pledges were, and were widely believed to be, genuine). Alternatively, an international or multinational nuclear force might be retained to deter or punish cheaters. Somewhat paradoxically, however, the implementation of such safeguards would require a degree of trust and cooperation that would be possible only if cheating by the cooperating states was considered highly unlikely.

One type of safeguard that might not require such dramatic improvements in international relations would be to allow nuclear-weapon states to maintain a capability to build nuclear weapons. States could, for example, be allowed to maintain a small stockpile of plutonium pits and other bomb components in separate storage areas, under international monitoring. An attempt by any state to retrieve these components would trigger alarms in other countries, leading them to assemble and disperse their nuclear weapons. The knowledge that any attempt to cheat or break out of the disarmament agreement would produce an instant and offsetting response by other states would deter cheating in the first place, because cheating could produce no lasting advantage. Maintaining the capacity to rebuild nuclear weapons also would remove the incentive for states to keep a few "bombs in the basement" as a hedge against the possibility that other states might do the same. It would be necessary to protect the bomb-building capacity of each state against preemptive attack by other states, of course, through a combination of multiple sites, deep burial, or provisions for rapid dispersal.

There are two potential problems with this type of safeguard arrangement, however. First, allowing states to maintain the capability to build nuclear weapons on short notice would make it easier for a state to cheat while at the same time making it more difficult to detect cheating. States would argue, for example, that they would need nuclear-weapon design laboratories, testing facilities, and facilities to produce tritium and fabricate weapon components. These activities would be of great value for a clandestine program, and would create a background of legal activity against which it would be more difficult to detect illegal activities. Second, having states poised to resume manufacture and deployment could create dangerous instabilities in which states might rush to rearm during a crisis. The possibility of rearming could lead states to disperse their weapon components to protect them from attack, worsening the crisis. If "rules of the road" could be developed to prevent such instabilities, then this sort of arrangement might be a useful way station on the path to a more complete elimination of nuclear-weapon capabilities.

In summary, it would be wrong to believe that nuclear disarmament would be adequately verifiable only when we had learned how to detect with high confidence every hidden bomb or every kilogram of hidden plutonium, and when we had figured out how to prevent or detect any diversion of nuclear materials from peaceful uses. Available verification techniques, if implemented vigorously in a spirit of cooperation, could verify the absence of large-scale cheating, but they could not rule out the possibility of "bombs in the basement" or rapid break-out. Nuclear disarmament will be possible not when small-scale cheating or break-out is impossible, but rather when nations become convinced that such cheating no longer seems very likely or very important. In the meantime, verification of the reductions process will play an essential role in moving us toward a world with the degree of trust and transparency necessary to make this possible.