Technical Aspects of Nuclear Proliferation

4

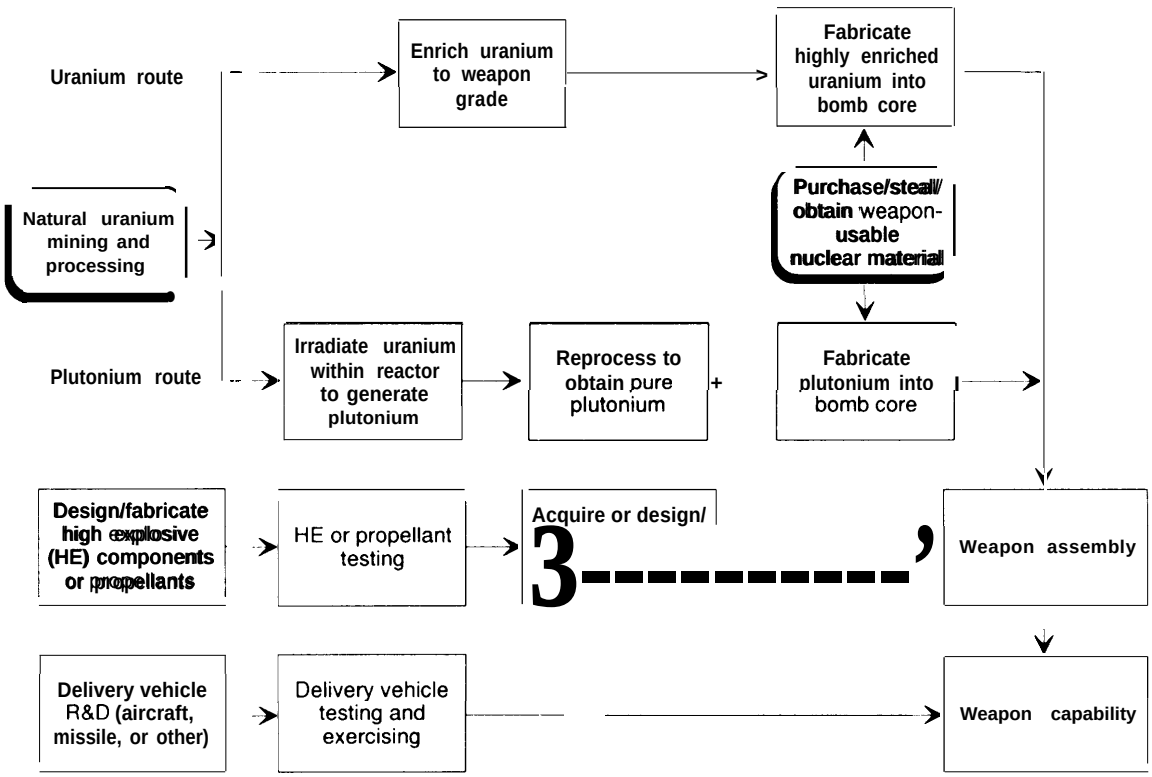
A wide variety of policy tools are available for combating nuclear proliferation, as described in the OTA Report *Proliferation of Weapons of Mass Destruction: Assessing the Risks.*[1] *Since these* measures depend at least in part on the technical prospects for monitoring and controlling nuclear proliferation, this chapter provides background on the difficulty and the detectability of nuclear weapon production. It describes the technical requirements for developing a nuclear weapon, identifying the steps that are the most difficult, time-consuming, or expensive, as well as those that are most amenable to external control. It also discusses detectable ''signatures' associated with each of these steps that might be used for monitoring or verification purposes.

To evaluate the proliferation risks posed by any particular country, however, or to determine which policies can most effectively reduce those risks, the technical hurdles described in general terms in this chapter must be considered in the context of the country's individual situation. In many cases, nontechnical considerations, rather than technical ones, may dominate not only whether a country decides to pursue nuclear weapons but also its likely success in doing so. These factors, *which are highly country-dependent,* include:

- the ability of a government to organize, manage, and carry through complex, long-term projects involving a large scientific and technological infrastructure, and to keep state secrets;
- a country's foreign business contacts, trade, and supply of hard currency; and

[1] U.S. Congress, Office of Technology Assessment, *Proliferation of Weapons of Mass Destruction: Assessing the Risks,* OTA-ISC-559 (Washington, DC: U.S. Government Printing Office, August 1993).

Figure 4-l—Technical Routes to a Nuclear Weapon Capability



SOURCE: Office of Technology Assessment, 1993.

- the domestic and international costs of getting caught, including possible diplomatic isolation and potential loss of trade, of technology transfer, or of foreign assistance.

Addressing such technical and nontechnical factors on a country-by-country basis, however, is beyond the scope of this report.

OVERVIEW AND FINDINGS

Manufacturing nuclear weapons, shown schematically in figure 4-1, is a complex and difficult process. It can be divided into three basic stages. The first, and most difficult, is the production of the special nuclear materials-plutonium, uranium-233, or enriched uranium-235—that are at the heart of a nuclear warhead. These materials can sustain nuclear chain reactions that release tremendous amounts of energy in a short period of time (see box 4-A for definitions of various nuclear materials). To manufacture highly enriched uranium-235 (HEU) for weapons, the uranium-235 isotope must be separated from the much more common uranium-238. A number of techniques can be used to enrich uranium, all of which to date involve complex and expensive facilities (see app. 4-B on enrichment technologies). Plutonium for weapons is derived from the naturally occurring uranium-238 isotope, which cannot be used directly in a nuclear weapon. However, irradiating uranium-238 in a nuclear reactor will convert part of it into plutonium-239, which can be used in nuclear weapons after it is separated from the unconverted uranium and other irradiation byproducts in a step called chemical reprocessing. Similarly, uranium-233 is

Box 4-A-Glossary of Nuclear Materials

Fertile material-an isotope that can be transformed into a fissile isotope by absorbing a neutron, such as when irradiated in a nuclear reactor. For instance, U-238 is a fertile (as well as fissionable, see below) material that tends to absorb slow neutrons, after which it decays into the fissile isotope Pu-239. Thorium-232 can similarly be transformed into U-233.

Fissile material-an isotope that readily undergoes fission (splits into two or more lighter elements, thereby releasing energy) after absorbing neutrons of any energy. Fissile materials can undergo self-sustaining nuclear chain reactions, in which the neutrons released in fission reactions will themselves induce additional fission reactions (most fissile materials emit two or more additional neutrons, on average, per fission). Important fissile isotopes are U- 233, U-235 and Pu-239. (Pu-241 is also fissile, but is normally created as a byproduct of Pu-239 production.)

Fissionable materitial isotope that undergoes fission only after absorbing neutrons above a certain energy. The most important fissionable material, U-238, emits less than one additional neutron, on average, per fission reaction; thus, although it can release additional energy when bombarded by neutrons of sufficient energy, it cannot sustain a nuclear chain reaction.

Highly enriched uranium (HEU)-uranium enriched in the isotope U-235 to 20 percent or more; often refers to enrichments above 80 percent, which are more useful for nuclear weapons. Uranium enriched to such levels will normally contain about 1 percent U-234, which is responsible for much of its radioactivity.

Low-enriched uranium (LEU)-uranium enriched in the isotope U-235 to less than 20 percent; often refers to enrichments of 2 to 5 percent, which are used to fuel t he most common type of commercial power nuclear reactor (“light-water reactors”).

Mixed oxide fuel (MOX)-nuclear reactor fuel composed of plutonium and natural or low-enriched uranium in oxide form ($U0_2$ and PuO_2. The plutonium component plays the role of the fissile U-235 isotope in LEU fuel, thus reducing the need for uranium enrichment. For instance, MOX fuel with a plutonium concentration of about 3 to 5 percent can substitute **for a portion of the low- enriched uranium fuel** in most types of nuclear reactor. (LEU-fueled reactors also make and burn plutonium as they operate, such that by the time LEU fuel is considered to be “used up,” it contains more plutonium than U-235.)

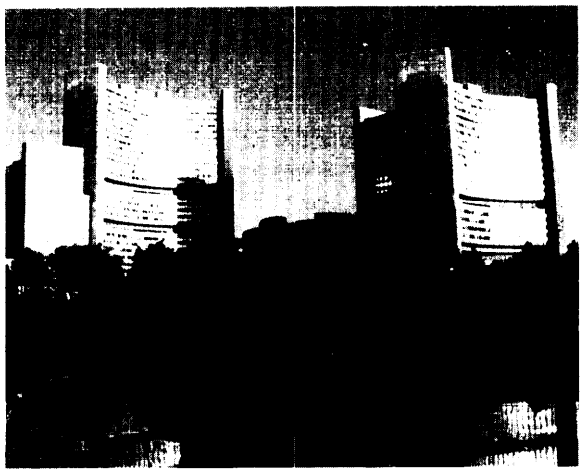
Natural uranium (Nat-U)-uranium of the isotopic concentration occurring in nature, in which about 0.7 percent is the isotope U-235, and 99.3 percent is U- 238. It also contains a trace of U-234.

Reactor-grade plutonium (RGPu)-plutonium that contains at least 20 percent of the nonfissile isotopes Pu-240 and Pu-242. RGPu is produced in most power reactors under normal operation, whereby fuel elements containing U-238 are exposed in the reactor to high neutron fluences for long periods of time (typically a year to a few years).

Weapon-grade plutonium (WGPu)-plutonium that typically contains 6 percent or less of the isotopes Pu-240 and Pu-242, isotopes that makes design of nuclear weapons increasingly more difficult. WGPU is created when U-238 is irradiated in a nuclear reactor for only a short period of time.

Yellowcake-uranium concentrate (with the isotopic ratio of natural uranium), which is produced from uranium ore through a process called “milling”; consists of about 80 percent U_3O_8; may also refer to U_3O_8 itself.

SOURCE: Office of Technology Assessment, 1993.


PETR PAVLICEK, IAEA

The Vienna International Center, housing the headquarters of the International Atomic Energy Agency.

produced by irradiating thorium in reactors (this path is not shown in figure 4-l). Neither the production of uranium-233 nor of plutonium requires enriched uranium.

To make the enriched uranium or plutonium into a weapon, various additional components must be added: chemical explosives (or in the case of gun-type weapons, propellants) to assemble the nuclear material into a super-critical mass that will sustain an explosive chain reaction; nonfissile materials to reflect neutrons and tamp the explosion; electronics to trigger the explosives; a neutron generator to start the nuclear detonation at an appropriate time; and associated command, control, and security circuitry (see app. 4-A on nuclear weapon design). In general, nuclear testing that involves a detonation of the resulting nuclear explosive device is not necessary for a competent designer to have high confidence that a relatively unsophisticated fission weapon will detonate, although nonnuclear testing of the chemical explosive system in an implosion-type weapon would be required. A gun-type weapon made with HEU would not even require chemical-explosive testing. Nevertheless, nuclear explosive testing would be much more important for a proliferant seeking to develop either very low-weight weapons, such as for delivery by missiles of limited payload, or thermonuclear weapons.

The third stage in developing a nuclear weapon capability is integrating the weapon with a delivery system and preparing for its use. Many of the states seeking nuclear weapons also seem to be developing ballistic missiles, and all already have combat aircraft. However, high-tech military systems are not required to deliver nuclear weapons; other military or civilian vehicles could also be used.

| International Controls

IAEA SAFEGUARDS

International efforts to control proliferation have traditionally focused on production of nuclear weapon materials, since that is the most difficult and the most visible (short of nuclear testing) of the processes necessary to make nuclear weapons. The Nuclear Nonproliferation Treaty of 1968 (NPT) requires non-nuclear-weapon member states to place all their nuclear materials under *safeguards:* a system of materials accountancy, containment, and surveillance administered by the International Atomic Energy Agency (IAEA) and supported by regular onsite inspections at declared facilities. IAEA safeguards (see app. 4-C) are intended to detect, and thereby deter, the diversion of such materials from declared peaceful purposes to weapons. Under the NPT, safeguards must be imposed on all nuclear materials possessed by non-nuclear-weapon state (NNWS) parties, transferred between NNWS parties, or transferred from any party to any nonparty.[2] The Treaty also

[2] The IAEA traditionally does not consider uranium ore or uranium concentrate to be ''nuclear material' for safeguards purposes until it is converted into a form suitable for further enrichment (e.g., uranium hexafluoride gas) or for fuel fabrication (e.g., oxide, metal, alloy, or carbide forms). IAEA safeguards also include an exception allowing declared nuclear material to be removed from safeguards for the purpose of military nonexplosive use, such as for submarine-propulsion reactors.

requires that no equipment ''especially designed or prepared for the processing, use, or production" of nuclear material shall be transferred by an NPT member to any nonnuclear-weapon state, even one not party to the NPT, unless all nuclear material processed by that equipment is placed under safeguards. By mandating the adoption of IAEA safeguards, the NPT is intended to permit states to pursue peaceful nuclear programs without giving rise to fears of nuclear weapon development.

Safeguards are important for all nuclear facilities, but especially for those dealing with enrichment or reprocessing. Many of the commercial facilities that enrich uranium for use in power plants, if reconfigured for higher enrichments, would be able to make highly enriched uranium for hundreds of weapons or more per year.[3] Moreover, several countries reprocess spent fuel from nuclear reactors to recover the plutonium generated during reactor operation, and even pilot-scale reprocessing plants can produce enough plutonium for weapons. Civilian nuclear fuel cycles that include the use of plutonium and its attendant reprocessing facilities could—if not safeguarded, or if safeguards were violated—be used to produce plutonium for large numbers of weapons. The type of plutonium produced in commercial nuclear reactors under normal operation, called reactor-grade plutonium, is more difficult to make into a weapon than plutonium produced specifically for weapons.[4] Nevertheless, reactor-grade plutonium can be used to make nuclear weapons of significant (though probably much less predictable) yield, and any state possessing significant quantities of separated plutonium should be considered to have the material needed to fabricate nuclear components for nuclear explosive devices in a short period of times

IAEA safeguards are designed, and to date have served, to make it very difficult to divert ''significant quantities' of nuclear materials from safeguarded facilities. (The IAEA defines a ''signtilcant quantity' of fissile material as 8 kg of plutonium or 25 kg of highly enriched uranium-see app. 4-C.) Indeed, the construction and operation of nuclear power reactors and other commercial facilities so as to divert materials to a weapon program is neither the easiest nor the most efficient route to obtain nuclear weapon materials. Moreover, by using modern equipment and measurement techniques, safeguards methods have been significantly improved and in many cases are becoming more automated, more tamper-resistant, and less intrusive to plant operation. Commercial-scale bulk-handling facilities such as fuel-fabrication plants, uranium-enrichment plants, and reprocessing facilities, which process large quantities of nuclear material in often dilute and easily modifiable aggregate form rather than in accountable units such as fuel rods or reactor cores, are more difficult to safeguard than individual nuclear reactors. However, at present there are no large facilities of this

[3] Almost all civilian power reactors use low-enriched uranium (LEU, see box 4-A), but the enrichment facilities that produce LEU might also be used to produce HEU. Reconfiguring some types of enrichment plants, such as gaseous diffusion plants, from producing LEU to producing HEU would be extremely time-consuming and virtually impossible to accomplish in a safeguarded facility without detection. On the other band, reconfiguring gas centrifuge plants could, in theory, be accomplished more easily. Institutional barriers, such as a state's own system of control and perceived best interests, must supplement technical ones as deterrents to any such reconfiguration.

[4] The states that have been known to or have sought to produce nuclear weapons have made a determined effort to produce weapon-grade materials specifically for that purpose; no military nuclear weapon program is known to have relied on reactor-grade plutonium.

[5] See, for example, J. Carson Mark, Reactor-Grade *Plutonium's Explosive Properties* (Washington, DC: Nuclear Control Institute, August 1990).

type under fulltime IAEA safeguards in countries of particular proliferation concern.[6]

Still, IAEA safeguards have fundamental limitations. First, several suspect nuclear proliferant states are not signatories to the NPT and are not obligated to place all their nuclear facilities under safeguards. Second, safeguards cannot prevent an NPT member from amassing a stockpile of nuclear weapon materials under safeguards, withdrawing from the NPT, and asserting that its stockpile is no longer subject to safeguards. Third, while the NPT clearly obligates member states to declare *all* of their nuclear facilities and place them under safeguards, it does not provide a "hunting license" to verify the absence of undeclared facilities. The IAEA does have the power to request "special inspections" at declared or undeclared facilities, should it find reason to do so, but no such inspections of undeclared facilities (except in Iraq) have ever been carried out.[7] Therefore, the NPT and the IAEA have very little ability to forestall the development of nuclear weapons in states that are not NPT members, and only limited ability in NPT member states that are able to develop a secret nuclear infrastructure outside IAEA safeguards. Indeed, the covert, indigenous production of nuclear materials is now most likely a greater danger than the diversion of nuclear materials from safeguarded facilities. Some of the signatures that might reveal such a covert program are discussed in this chapter.

EXPORT CONTROLS

Export controls constitute the other primary means (besides IAEA safeguards) by which the international community can seek to prevent proliferant states from acquiring the technical capability to develop nuclear weapons. (Most other nonproliferation policies address the incentive, and not the capability, to develop nuclear weapons .8) One form of export controls is imposed by the NPT, which forbids the transfer of equipment designed to process nuclear materials unless it is placed under IAEA safeguards. The NPT also prohibits nuclear-weapon states from exporting goods or information that would assist in any way with the development by non-nuclear-weapon states of nuclear weapons.

If, despite the NPT, a state were able to import unsafeguarded nuclear material suitable for weapons—perhaps from the former Soviet Union or from a proliferant state already possessing enrichment or reprocessing facilities-it would obviate the need to produce its own weapon material. Such transfers would leapfrog the bulk of the international technical controls against proliferation. Transfers of low-enriched uranium are not nearly so dangerous, since they do not eliminate a proliferant state's need to develop complex enrichment facilities. However, if a proliferant already has such facilities, feeding them with LEU rather than natural uranium can easily more than double their capacity to produce weapon-grade uranium.

Jolted by India's "peaceful nuclear explosion' in 1974, several industrialized countries collec-

---

[6] Note that only facilities under *full-time* safeguards are considered here, since those not safeguarded or safeguarded only part of the time (e.g., when safeguarded fuel is present) cannot be expected to be verifiably free from diversion at other times. (Argentina and India, for instance, have some nuclear facilities under part-time safeguards, and Kazakhstan has a fuel-fabrication plant not yet under safeguards, though it is moving toward accession to the NPT and thus to full-scope safeguards.) Brazil has a medium-size fuel-fabrication facility under IAEA safeguards and, with South Africa's accession to the NPT, that country's enrichment facilities are also being placed under full-scope safeguards. But neither state is considered a first-order proliferation threat at present.

[7] The IAEA's first attempt at requesting such a special inspection was directed at North Korea in early 1993 and was refused. Subsequently, the IAEA declared North Korea to be in violation of its safeguards agreement and referred the matter to the United Nations Security Council, which is addressing the issue. As of November 1993, the dispute was still under negotiation.

[8] Incentives and other policy tools, such as security guarantees, cooperation and development assistance, regional arms control, and threats of U.N. or other intervention, are introduced in ch. 3 of the OTA report *Proliferation of Weapons of Mass Destruction; Assessing the Risks,* op. cit., footnote 1.

tively decided to impose export controls that would extend beyond those required by the NPT. Forming the Nuclear Suppliers Group in 1975, these countries initially agreed to exercise restraint on the transfer of any goods or systems directly applicable to the production of nuclear weapon materials (e.g., nuclear reactors and reprocessing equipment for separating plutonium, or systems such as gas centrifuges or gaseous diffision systems for enriching uranium).[9] As a result, the export of most such systems today is tightly constrained. Together with the required imposition of IAEA safeguards, these controls have made it very difficult for would-be proliferant states to acquire "turn-key" systems to produce nuclear weapon materials. However, technologies for some older enrichment methods (e.g., the calutrons for electromagnetic separation, used by Iraq) and some components for not-yet-commercialized methods (e.g., lasers useful for research on some advanced separation techniques) have been more easily obtainable. Moreover, rather than importing complete systems to produce nuclear materials, some proliferant states now possess and others are attempting to build their own equipment, drawing on "dual-use' technologies such as high-voltage power supplies, high-strength alloys and carbon-fiber products, high-performance ion-exchange resins and liquid-liquid contacting equipment, precision machine tools, welding equipment, and specialized furnaces that also have legitimate civil (nonnuclear) applications. Spurred largely by Iraq's progress toward nuclear weapons as revealed after the Persian Gulf War of 1991, the 27 countries of the Nuclear Suppliers Group recently extended their controls to include a wide array of ''dual-use' technologies (see app. 4-D), thus closing many loopholes in previous nuclear export controls.

Computers are an important class of dual-use goods, having widespread applications in civil as well as weapon-related fields. Useful as they may be for nuclear weapon development, however, advanced high-performance computers (so-called '' supercomputers '' in the 1980s) are *by no means necessary* for design of first-generation fission weapons even in the absence of nuclear testing; placing strict limits on their exports would be of only secondary importance compared to limiting technologies for nuclear-materials production. Computers of lesser capability are more than adequate for first-time proliferants and are becoming increasingly difficult to control as their production spreads around the world. However, advanced computers are relatively more important for proliferants pursuing advanced nuclear weapons, including thermonuclear ones.

In addition to nuclear materials and weapon-related technology, expertise is a key ingredient in making nuclear weapons. Although specific details remain secret, basic *principles* of nuclear weapon design have been widely known for decades and cannot be controlled. Moreover, the progress made by successful nuclear proliferants shows that dedicated research programs can fill in the engineering details. First-time proliferants in the 1990s could and probably would build nuclear weapons considerably smaller and lighter than the first U.S. weapons. Nevertheless, "weaponizing" a nuclear warhead for reliable missile delivery or long-term shelf-life adds additional technical difficulties and could significantly increase the research and development efforts needed to field it. Should they offer their services, skilled weapon designers from the acknowledged nuclear powers could significantly accelerate the progress of a proliferant's nuclear program, primarily by steering it away from unworkable designs. They would also be particularly significant in the fields of isotope-separation

[9] Not only are these export controls not mandated by the Nuclear Non-Proliferation Treaty, but many countries, particularly developing states, argue that they violate the NPT obligation upon industrialized states to participate in "the fullest possible exchange of equipment, materials and scientific and technological information for the peaceful uses of nuclear energy' (NPT, Article IV, Section 2).

techniques or plutonium production. Such individuals could fill critical gaps in a proliferant's knowledge or experience, adding greatly to the likelihood that its programs would succeed. They could also increase the range of sophistication of designs feasible without testing. Therefore, continuing to protect subtle weapon design details and preventing experienced weapon-system scientists and engineers from emigrating or selling their services to proliferant states will be important adjuncts to export-control policy.

| Difficulty and Detectability of Nuclear Proliferation

Producing nuclear weapon materials indigenously would require at least a modest technological infrastructure and hundreds of millions of dollars to carry out. The costs of a full-scale indigenous program, however, especially if clandestine and lacking outside nuclear-weapon expertise, can be as much as 10 to 50 times higher than for a program aimed at producing just one or two bombs and largely carried out in the open or with outside technical assistance. Prior to the Gulf War, Iraq spent many *billions* of dollars-over 20 times the cost of a minimal program-to pursue multiple uranium-enrichment technologies, to build complex and sometimes redundant facilities, to keep its program as secret as possible, and to begin to lay the foundation for a fairly substantial nuclear capability. Few countries of proliferation concern could match the resources that Iraq devoted to its nuclear weapon program. (Iran probably could, however, if it so chose.)

In the near term, low- and medium-level gas centrifuge technology may become increasingly attractive to potential proliferants, for reasons including the availability of information on early-model centrifuge design, the widespread use of and possible illicit access to know-how for more advanced centrifuge technology, and the relative ease both of hiding centrifuge facilities and using them to produce highly enriched uranium (HEU). The more advanced centrifuge technology, once obtained, could lead to small, efficient, and relatively inexpensive facilities that would be particularly difficult to detect remotely.

Because of their small size and potential for high enrichment in few stages, laser isotope enrichment techniques could prove to be difficult to detect and control if successfully developed in a clandestine program.[10] Nevertheless, except in the advanced industrial countries, constructing operational laser-enrichment facilities will remain very difficult. *(Industrial-scale* facilities remain difficult even for the advanced countries.) Therefore, it is unlikely for at least another decade that these technologies would play a significant role in nuclear programs of developing countries.

The published data and recent successes in **Japan and** France, respectively, with ion-exchange and solvent-extraction enrichment methods relying on conventional chemical-engineering processes, make these techniques potentially a more serious proliferation concern than they had previously been thought.

Aerodynamic enrichment techniques, which use carefully designed nozzles or high-speed gas flows to separate isotopes by mass, have been successfully developed by Germany and South Africa. Some aerodynamic techniques require fairly sophisticated technology to manufacture precision small-scale components, but are otherwise conceptually straightforward and are capable of producing HEU.[11] If strict controls are not maintained on these technologies, they could pose proliferation risks.

Gaseous diffusion technology, developed by each of the five declared nuclear powers, forms

10 Laser enrichment technologies use precisely tuned laser beams to selectively energize the uranium-235 isotope most useful for nuclear weapons and separate it from the more common uranium-238 isotope (see app. 4-B on enrichment technologies).

11 A principal difficulty in constructing aerodynamic enrichment facilities, however, is obtaining pumps, seals, and compressors that are resistant to uranium hexafluoride.

the basis for much of the world's current enrichment capacity, but it has proven difficult for other countries to develop and does not appear to be as likely to be pursued by proliferant states as some other methods.

The process of acquiring or constructing the appropriate facilities and then producing nuclear weapon materials in them provides many signatures and the greatest opportunity for detecting a clandestine nuclear weapon program. The development and testing of nuclear weapon *components* provide significantly fewer observable indicators. Assembly and deployment of a small number of weapons themselves might similarly not be easily detected, although specialized preparations for aircraft or missile delivery might be more readily seen. Deploying large numbers of nuclear weapons, however, might call for new military doctrine and elaborate training, security, and support systems, thus increasing the number of people involved and the possibility that information about the program might be leaked. Sufficiently large nuclear tests (possibly at the kiloton level; certainly at the 10 kt level) would probably be detectable by various means, but they are not necessary for fielding first-generation fission weapons with reasonably assured yields.

Iraq and South Africa demonstrated that with enough effort and financial resources, a country can hide from international view both the size and specifics of its nuclear weapon program-though certainly not all evidence of its existence, Iraq, for example, though party to the NPT, clandestinely pursued an ambitious program outside of safeguards, while maintaining a massive internal organization and extensive and carefully developed channels of foreign technical assistance (many of which have now consequently been subject to more stringent controls). Therefore, although technology restrictions can retard proliferation, and verification procedures and monitoring technologies can help detect and thus deter proliferation, the primary barriers to proliferation of nuclear weapons in the long term remain institutional rather than technological. A state's perception of its own security and national interests, and whether it believes a nuclear weapon program would serve those interests or detract from them, play major roles in the decision process.

ACQUIRING NUCLEAR WEAPON CAPABILITY

For most of the nuclear age, purchasing or stealing nuclear weapons has been relatively easy to dismiss, since the nuclear powers controlled their weapons very tightly. However, the collapse of the Soviet Union for the first time has posed real concerns over the security of nuclear weapons themselves, as well as over weapon materials, components, design information, related technology, and expertise.[12] The following section addresses the potential diversion of Soviet nuclear weapons; it is followed by a discussion of the more traditional problem of preventing states from manufacturing their own nuclear weapons.

"Loose Nukes" in the Former Soviet Union

Various unconfirmed reports in the first months of 1992 in the European press and elsewhere claimed that Iran had purchased several tactical nuclear warheads or their components from one or more newly independent Islamic republics of the former Soviet Union.[13]

12 See, for example, Oleg Bukharin, *The Threat of Nuclear Terrorism and the Physical Security of Nuclear Installations and Materials in the Former Soviet Union,* Occasional Paper No. 2 (Monterey, CA: Center for Russian and Eurasian Studies, Monterey Institute of International Studies, August 1992).

13 See, for example, Yossef Bodansky, "Iran Acquires Nuclear Weapons and Moves to Provide Cover to Syria," *Defense and Foreign Affairs Strategic Policy,* February *1992,* Special Section, pp. 1-4; and FBIS, WEU-92-054-A, Mar. 19, 1992 (about a report in the Mar. 15, 1992 issue of the German magazine *Stern).*

Since nuclear artillery shells, short-range rockets, aerial bombs, and other tactical weapons intended for battlefield use are readily portable, such reports are cause for concern. Nevertheless, senior Russian intelligence officials have claimed that they know where every one of their weapons is and that none is missing.[14] Furthermore, U.S. officials have said, without asserting that they know the whereabouts of every Soviet nuclear weapon, that they are not aware of any independent evidence corroborating such transfers.[15] Past attempts to purchase nuclear warheads, such as by Libya from China, have been reported, but never known to be successful.[16]

By mid-1992, according to Russian officials and later supported by CIA director R. James Woolsey in congressional. testimony,[17] all tactical nuclear weapons had been returned to Russia from non-Russian republics. However, since the political situation in Russia is far from settled, removing nuclear weapons from the other republics to Russia does not resolve questions concerning the weapons' security. Moreover, strategic weapons—the higher yield, bulkier weapons designed for intercontinental missile or bomber delivery-are still based in three non-Russian republics (Ukraine, Belarus, and Kazakhstan), raising questions over the: ultimate status of these republics as nuclear or non-nuclear powers.

Even if whole nuclear weapons were transferred to a non-weapon state, it is unlikely in most circumstances that they could be detonated in their present form. All strategic and many tactical weapons in the former Soviet Union are believed to be configured with "permissive action links" (PALs) or equivalent controls that preclude their direct detonation except upon introduction of a special code.[18] However, the level of sophistication of Soviet PALs is not known, and many—especially early models-may be comparatively rudimentary, not integral to the weapon, or entirely absent.[19] Such devices cannot be presumed to delay indefinitely a technically sophisticated individual or team that had prolonged access to the weapon.

Moreover, a smuggled weapon would constitute a serious danger even if it could not be detonated. First, disassembly by suitably trained individuals could provide valuable first-hand information on its design, materials, and components. Second, the weapon's nuclear materials might be recovered for use in another weapon. As such, transfer of any warhead to any nonweapon-state would be cause for serious concern, even if its immediate utility as a detonable device were low.

Manufacturing Nuclear Weapons

Aspiring proliferants unable to purchase or steal nuclear weapons, or unwilling to rely on so limited an arsenal, would have to manufacture them on their own. The following sections

---

14 Paul Quinn-Judge, "In Republics, An Eye on Bombs, Scientists," *Boston Globe,* June 23, 1992, p. A14; and Mary Curtius, "U.S. Seeks to Stop Stockpile Leaks," *Boston Globe,* June *24, 1992,* p. *22.*

15 See, for example, R. James Woolsey, Director of Central Intelligence, testimony before the Senate Committee on Governmental Affairs, Feb. 24, 1993.

16 Leonard S. Spector with Jacqueline R. Smith, *Nuclear Ambitions: The Spread of Nuclear Weapons, 1989-1990* (Boulder, CO: Westview Press, 1990), pp. 175, 178, and references therein.

17 Testimony of R. James Woolsey, Feb. 24, 1993, op. cit., footnote 15.

18 Kurt M. Campbell et al., *Soviet* Nuclear Fission: *Control of the Nuclear Arsenal in a Disintegrating Soviet Union,* CSIA Studies in International Security, No. 1 (Cambridge, MA: Center for Science and International Affairs, Harvard University, November 1991), pp. 13-17. Although the first PALs used on U.S. weapons were simple mechanical combination locks, subsequent designs have become more sophisticated; many now include disabling devices that, upon attempts at unauthorized intrusion, can destroy critical warhead components, rendering the warhead undetonable. Warheads also traditionally include environmental sensing devices, which, although more easily bypassed than intrusion sensors in PALS, enable the warhead to detonate only after it undergoes the proper stockpile-to-target or launch sequence (e.g., changing barometric pressure, acceleration, etc.).

19 Ibid., p. 15.

describe and analyze the various steps required to produce nuclear weapons, identfying the points at which international nonproliferation efforts might have the greatest leverage.

This chapter focuses on *covert* nuclear weapon programs. Since 1964, when China detonated its first nuclear device, no country has openly advertised developing a nuclear weapon capability, even though several states are suspected of having mounted nuclear weapon programs since then.[20] India, a non-NPT state, detonated a so-called ''peaceful nuclear device' in 1974, but denies having a nuclear weapon program. Evidently, international norms against nuclear proliferation (or the reactions of regional adversaries) have been sufficient to prevent emerging nuclear powers-even those not members of the NPT—from advertising their programs too openly .21

A successful proliferant must overcome a number of technical hurdles. Among them are: obtaining enough fissile material to form a super-critical mass for each of its nuclear weapons (thus permitting a chain reaction); arriving at a weapon design that will bring that mass together in a tiny fraction of a second, before the heat from early fissions blows the material apart; and designing a working device small and light enough to be carried by a given delivery vehicle. These hurdles represent *threshold requirements: unless* each one is adequately met, one ends up not with a less powerful weapon, but with a device that cannot produce any significant nuclear yield at all or cannot be delivered to a given target. Table 4-1 and figure 4-1 outline the steps required to produce and deploy nuclear weapons. Both the figure and the table show the two basic approaches for acquiring nuclear materials: enriching uranium to highly enriched levels, or irradiating uranium in a nuclear reactor followed by reprocessing to separate out the plutonium.[22] They also portray the weapon design, fabrication, and deployment stages.

SOURCES OF NUCLEAR MATERIALS

A potential proliferant has three options for acquiring fissile material needed for a nuclear weapon: purchase or theft, diversion from civilian nuclear activities in violation of IAEA safeguards, or indigenous production in unsafeguarded facilities. Each of these routes is prohibited to NPT non-nuclear-weapon states and to states that are parties to nuclear-free-zone treaties such as the Treaty of Tlatelolco; such states are prohibited from operating unsafeguarded nuclear facilities. Any unsafeguarded facilities that such states did operate would presumably be run covertly. Non-NPT states such as Israel, India, and Pakistan are under no treaty obligations to refrain from acquiring, producing, or selling fissile materials or to place all their nuclear production facilities under IAEA safeguards (some come under safeguards when processing safeguarded material supplied by NPT states), but they might well seek to keep unsafeguarded activities secret anyway.

Indigenous production of weapon-grade nuclear material requires a large, complex, and expensive set of specialized facilities, and the

---

20 Evidence Of a country's decision to ''go nuclear'' need not be dramatic, as it was with the inspections in Iraq following the 1991 Gulf War, with Mordecai Vanunu's revelations about Israel's nuclear program, or with India's "peaceful" detonation in 1974. Instead, evidence of a country's potential intent and capability can unfold slowly over tie. The latter has been the case with North Korea and@ and before they opened up their facilities to safeguards, with South Africa, Argentina, and Brazil. South Africa's program was subsequently also revealed in a more dramatic fashion by President F.W. de Klerk, when he announced in March 1993 that South Africa had assembled six nuclear weapons in the 1980s.

21 Many nonproliferation specialists, however, worry that an open nuclear arms race may erupt between India and Pakistan, both of which are "threshold" states considered either to have nuclear weapons or to have the capability to construct them on short notice.

22 Thorium can &SO be irradiated in nuclear reactors to produce the fissile isotope uranium-233, which can then be separated for use in nuclear weapons by chemical reprocessing similar to that for plutonium. However, thorium-based fuel cycle technology has not been developed to the point where it would present a likely proliferation route.

Table 4-I-Steps to Produce and Deploy Nuclear Weapons

Acquisition of nuclear weapon materials
- **Mining of uranium-bearing ore**
- **Milling to extract uranium concentrate in the form** of "yellowcake" (U_3O_8) or other uranates[a]
- Chemical processing to convert yellowcake into **useful compounds (such as UO_2, UF_6, UF_4, UCl_4)**

-Uranium-235 *based weapons:*
- , **Enrichment of uranium to high levels of uranium-235 (most often carried out** using uranium hexafluoride, UF_6, or other uranium compounds)
- Conversion of enriched uranium product to uranium metal

---Plutonium-based weapons:
- **Uranium fuel fabrication in the form of metal or oxide (using alloys, ceramics, zircalloy or aluminum cladding, etc.)**
- **Reactor construction and operation (typically requiring a graphite or heavy-water moderator[b], unless enriched uranium fuel were available)**
- **Reprocessing of spent fuel to extract plutonium product**
- **Conversion of plutonium product to plutonium metal**

Weapon fabrication (plutonium or uranium weapons)
- **Design and fabrication of fissile core**
- **Design and fabrication of nonnuclear components (chemical explosives, detonator, fuze, neutron initiator, reflector, etc.)**
- **Weapon assembly**

Weapon testing and deployment
- **Physics tests (hydrodynamic, hydronuclear, or nuclear—see text)**
- **Development of delivery system and integration with warhead**
- **Weapon transport and storage**
- **Possible development of doctrine and training** for use

a U_3O_8 can also be purchased on the international market; transfers to or from NPT parties with safeguards agreements in force must be reported to the IAEA, but do not require inspections.

b The moderator in a nuclear reactor slows down the neutrons produced in fission reactions so that they can more efficiently induce subsequent fission reactions. Heavy-water and ultra-pure graphite are effective neutron moderators having very low neutron absorption, thus permitting reactors to operate on natural uranium.

SOURCE: Stephen M. Meyer, The *Dynamics of Nuclear Proliferation,* **(Chicago, IL: Univ. of Chicago Press, 1984), p. 175; and OTA.**

relevant facilities therefore represent principal "chokepoints" for controlling nuclear proliferation. Unless a state succeeded in importing or otherwise acquiring weapon-usable material directly, producing such material in dedicated facilities is likely to cost many times what it would cost to design and fabricate other nuclear weapon components. Moreover, the nonnuclear development work could be funded and carried out well in advance of the supply of suitable nuclear materials (as was the case in Iraq), and it is much harder to monitor and control than nuclear material production.

This section discusses various sources where nuclear materials might be stolen or diverted to weapon use; it is followed by a discussion of requirements for manufacturing such materials indigenously.

Diversion or Theft

Nuclear materials, some of which are relatively easy to convert into forms directly usable in nuclear weapons, are stored at and transported among hundreds of civilian nuclear facilities around the world. These stockpiles and transfers inevitably introduce some risk of theft or diversion, depending on the material and the level of its protection. Theft of weapon-grade nuclear materials would be more serious than that of material

requiring substantial additional processing. If a particular stockpile were poorly safeguarded, diversion of material might not be detected before it had already been fabricated into a weapon. Such a clandestine diversion would probably constitute a greater danger than the hijacking of a shipment, which would certainly be noticed and might trigger military or other action to recover the stolen material or prevent its being used.

The low-enriched uranium (LEU) that fuels hundreds of nuclear power reactors worldwide cannot be used directly to make nuclear weapons. If used instead of natural uranium as a feedstock for a proliferant state's own uranium enrichment program, however, it can speed up considerably the production of highly enriched uranium for weapons. Furthermore, civilian nuclear reactors convert part of their uranium fuel into plutonium as they operate.[23] When separated from the unconsumed uranium fuel and the radioactive by-products produced during reactor operation—a step called *reprocessing—the* plutonium so obtained can be reused in nuclear reactors. However, it can also be used to make a weapon. By the year 2000, hundreds of tonnes of plutonium will have accumulated worldwide in civilian spent fuel, and with current plans, over 100 tomes will have been separated and stored. This potential coupling between civil nuclear power and nuclear weapons is a fundamental reason for the International Atomic Energy Agency's system of nuclear safeguards (see app. 4-C).[24]

Due in part to IAEA safeguards, individual commercial power reactors are neither the most vulnerable nor the most fruitful sites for diverting nuclear materials. Several possible sources of nuclear materials described below pose greater risks of theft or diversion than do commercial nuclear power reactors. Similarly, facilities where nuclear materials are handled in *bulk* (enrichment, fuel-fabrication, and reprocessing plants) pose substantially greater diversion risks than do commercial power reactors, but are consequently inspected much more often. In any case, there are no large bulk-handling facilities under full-time safeguards in countries of current proliferation concern.[25]

REACTOR-GRADE PLUTONIUM AND NUCLEAR WEAPONS

Reactor-grade plutonium recovered from civilian reactors differs from weapon-grade plutonium in the relative proportions of various plutonium isotopes (see box 4-B). Reactor-grade plutonium has a higher rate of spontaneous fission reactions

---

23 Reactors containing significant amounts of uranium-238 produce plutonium at a rate of about 1 gram per day per megawatt-thermal (MW(t)) of reactor power, or about 10 kg per year for a 30-MW(t) reactor running **90% of the time. Note that commercial reactors are** usually rated in terms of the *electrical* power they produce, in units of megawatts-electric (MW(e)), whereas research reactors and plutonium-production reactors are rated in terms of overall thermal power, MW(t). Since about two-thirds of the power used to generate electricity y becomes waste heat, a typical large commercial nuclear power plant that generates 1,000 MTV(e) would have a thermal power *of* **about 3,000** MW(t).

24 The 1977 OTA report *Nuclear Proliferation and Safeguards,* OTA-E-48 (Washington DC: U.S. Government Printing Office, June 1977), and appendices, vol. 2, parts 1 and 2, discusses the relationship between nuclear power, nuclear weapons, and international safeguards. The U.S. Department of Energy presented a detailed technical assessment of these relationships in Nuclear *Proliferation and Civilian Nuclear Power, Report of the Nonproliferation Alternative Systems Assessment Program* (NASAP), DOE/NE-0001/1, vols. 1-9, June 1980. Other references discussing nuclear safeguards include ''Materials Management in an Internationally Safeguarded Fuels Reprocessing Plant,'' *Los Alamos Scientific Laboratory Report IA-8042,* vols. I-III (April, 1980); David Fischer and Paul Szasz, *Safeguarding the Atom: A Critical Appraisal* (London: SIPRI, Taylor and Francis, 1985), especially ch. 7 and apps. II and III; Lawrence Scheinman, *The International Atomic Energy Agency and World Nuclear Order* (Washington DC: Resources for the Future, 1987), especially chs. 4 and 5; *IAEA Bulletin,* for example, vol. 32, No. 1 (1990); and *Journal of Nuclear Materials Management,* for example, vol. 20, No. 2 (February 1992).

25 India operates reprocessing facilities that are under safeguards only when reprocessing safeguarded uranium fuel. This leaves India, a non-NPT state, with the capability to separate plutonium for weapon use with this facility at other times. North Korea's alleged reprocessing facility at Yongbyon has been declared to the IAEA but has not yet been fully placed under safeguards. Brazil has a medium-sized fuel fabrication facility under IAEA safeguards, and South Africa's enrichment facilities have come under safeguards with its accession to the NPT, but neither state is considered a first-order proliferation threat at present.

than weapon-grade, generating neutrons that can initiate the nuclear chain reaction during weapon detonation sooner than would be optimal. As a result, using reactor-grade plutonium in a first-generation nuclear weapon can significantly reduce both the predictability and the expected yield of a weapon designed by a proliferant state.

None of the states that have either made nuclear weapons or attempted to do so appear to have selected anything but high-quality plutonium or uranium for their designs. Nevertheless, from a technical perspective, reactor-grade plutonium can be used to make nuclear weapons (see box 4-B), and any state possessing significant quantities of separated plutonium should be considered to have the material needed to fabricate nuclear components for nuclear explosive devices in a short period of time.

REPROCESSING PLANTS AND SEPARATED PLUTONIUM

Several hundred tonnes of weapon-grade plutonium will likely be recovered from dismantled U.S. and Russian warheads over the next decade and stored at facilities in those two countries .26 In addition to this plutonium, large quantities of separated plutonium *from civilian* reactors around the world continue to accumulate and be stored at four principal reprocessing sites: La Hague and Marcoule in France, Sellafield in Britain, and Chelyabinsk in Russia.[27]

Reactor-grade plutonium separated from spent fuel can be used either in a new generation of civilian reactors designed especially to use plutonium fuel, or in conventional nuclear reactors, where it can substitute for the uranium-235 in some portion of the LEU fuel.[28] However, unless the utilization of separated plutonium increases dramatically, it is almost certain that the current surplus of over 70 tonnes of stored separated plutonium will increase by another 100 tonnes by the year 2000.[29] Eventually, most of the foreign-owned plutonium at the sites in France and the U.K. is contractually obliged to be returned to its countries of origin-most of whom are not nuclear weapon states[30]—thus significantly increasing the transport and handling of plutonium around the world. By the end of the century, an additional several hundred tonnes of unseparated plutonium worldwide will also have accumulated in spent reactor fuel.[31]

---

26 See U.S. Congress, Office of Technology Assessment, *Dismantling the Bomb and Managing the Nuclear Materials*, OTA-O-572 (Washington DC: U.S. Government Printing Office, September 1993). Safeguarding the storage and ultimate disposition of nuclear materials from dismantled weapons in the former Soviet Union is a high U.S. priority and is the subject of intense ongoing discussions with Russia.

27 Small commercial reprocessing facilities are also operating at Tokai-mura in Japan and Tarapur in India, and have operated in the past in the United States (West Valley, New York), Germany (Karlsruhe), and Belgium @roch6mic-Mel). India is building an additional facility at Kalpakkam, possibly to begin operation in 1993-94, and Japan is planning to finish constructing a major reprocessing facility at Rokkasho-mura by about 2005. Reprocessing facilities for separating Russian *military* plutonium are located at two additional sites: Tomsk-7 and Krasnoyarsk. See Frans Berkhout et al., "Disposition of Separated Plutonium," *Science & Global Security*, vol. 3, No. 1, 1992, table 2, p. 7.

28 Plutonium for use in conventional nuclear reactors is usually combined with natural or low-enriched uranium in their oxide forms (UO_2 and PuO_2) to make mixed-oxide fuel or MOX. MOX having a plutonium concentration of about 3 to 5% of the uranium concentration can be used to replace about a third of the fuel rods in some types of conventional light-water reactor. Fast breeder reactors (FBRs) fueled primarily by plutonium are currently being developed by Japan, China, and Kazakhstan. France (which has shut down its Superphénix breeder reactor) and the U.K. are no longer as actively involved with breeder development as they had been in the past.

29 Prior t. 1991, about 120 tomes of civilian RGPu had been separated worldwide at the four facilities mentioned, of which 37 tonnes had been recycled in advanced liquid-metal reactors (mostly in demonstration breeder reactors) and another 12 tonnes as MOX fuel for conventional light water reactors (LWRs). From 1991 through 2000, another 190 tomes are contracted to be separated, primarily at reprocessing plants in Great Britain, France, and Japan, of which only about 70-80 tonnes are expected to be recycled in reactors.

30 These countries include Belgium, Finland, Germany, Italy, Japan, Netherlands, and Switzerland.

31 Frans Berkhout, Anatoli Diakov, Harold Feiveson, Marvin Miller, and Frank von Hippel, ' 'Plutonium: True Separation Anxiety,'' *Bulletin of the Atomic Scientists*, vol. 48, No. 9, November 1992, pp. 28-34.

Box 4-B—Reactor-Grade Plutonium

Plutonium produced in a reactor continues to be exposed to neutrons until the fuel is removed from the reactor. This prolonged exposure results in the buildup of other plutonium isotopes (atomic numbers 238,240,241, 242) in addition to plutonium-239.[1] The even isotopes of plutonium have a high probability of spontaneous fission and thus neutron emission, plus several other deleterious neutronic effects in weapons. By current U.S. definition, reactor-grade plutonium contains at least 20 percent even (non-fissile) isotopes, whereas weapon-grade contains 6 percent or less.

Because the non-239 plutonium isotopes are more radioactive and emit more spontaneous neutrons, they make the design of a plutonium weapon more difficult (virtually Impossible at high concentrations of Pu-238). The problems are at least two-fold. From the perspective of bomb performance, if too much plutonium-240 or -242 is present its spontaneous neutrons have a high probability of starting the chain reaction too soon, thus substantially reducing the yield. Second, reactor-grade plutonium generates 6 to 10 times more heat per unit mass than does weapon-grade plutonium,[2] and an IAEA significant quantity of RGPu (8 kg) would generate well over 100 watts of heat.[3]

Nevertheless, the critical mass of RGPu is only about 25 percent higher than that of weapon grade, and nuclear explosive devices can be designed that use it.[4] Plutonium with a nonfissile concentration (plutonium 240 plus 242) as high as 50 percent-as might be recovered from very high burn-up LEU fuel or MOX fuel-can also be used to make explosive devices having kiloton yields?

---

1 Although 65 percent of the neutrons captured by plutonium-239 cause it to fission, the remaining 35 percent are absorbed to create plutonium-240. Other higher isotopes are formed similarly. Reactor-grade plutonium normally continues to be exposed in a reactor for up to a few years. Weapon-grade plutonium is produced from uranium-238 that is exposed for only a relatively short the, possibly on the order of weeks.

2 Plutonium recovered from spent LEU or MOX fuel after 10 years of storage generates 14 to 24 W/kg-Pu, whereas weapon-grade plutonium generates only 2.4 W/kg-Pu. *Plutonium Fuel: An Assessment* (Paris: OECD/NEA, 1989), tables 9,128, as cited in Frans Berkhout, Anatoli Diakov, Harold Feiveson, Helen Hunt, Edwin Lyman, Marvin Miller, and Frank von Hippel, "Disposition of Separated Plutonium," *S&me& Global Security, vol.* 3, No. 1,1992, p. 10.

3 If this much RGPu were left surrounded with high explosive of low thermal conductivity, such as in an implosion device, it could generate temperatures above 200 "C, depending on the design.

4 See J. Carson Mark, Reactor-Grade *Plutonium's Explosive Properties* (Washington, DC: Nuclear Control institute, August 1990).

5 Alex DeVolpi, "Fissile Materials and Nuclear Weapons Proliferation," *Ann. Rev. Nucl. Part. Sci.*, vol. 36, p. 108 (table 4), In addition, based on declassified information, Maj. Gen. Edward B. Giller, deputy assistant administrator for national security for the U.S. Energy Research and Development Administration, stated in September 1977 that the U.S. detonated a nuclear device in 1962 using low-grade plutonium typical of that produced by civilian power plants (Robert Gillette, "Impure Plutonium Used In '62 A-Test," *&s Angeles Times, Sept.* 16, 1977, p. A3), thus providing experimental confirmation that such material could be used to build an atomic weapon. (Neither the isotopic composition of the plutonium used nor any yield information was released; at the time, reactor-grade plutonium was defined to contain greater than 8 percent of the isotopes Pu-240 and Pu-242.) See atso Paul Leventhal, "Weapons-Usable Nuclear Materials: Eliminate Them?" In *Director's Series on Proliferation*, Kathleen C. Bailey, cd., Lawrence Livermore National Laboratory, UCRL-LR-1 14070-1, June 7,1893, p. 34.

Box 4-C-Japanese Shipments of Separated Plutonium

After two decades of shipping spent fuel to Europe for reprocessing and storage, Japan has now begun a major program to ship back large quantities of separated plutonium from its LWR spent-fuel. Shoe the United States originally supplied this fuel, it has the right under the revised 1987 U.S.-Japan Nuclear Cooperation Agreement to approve or reject the final security plans for the shipments. Current plans call for up to30 or40 tonnes of separated plutonium to be returned to Japan by the year 2000, using four or five shipments per year.

Since the early 1980s, shipments of plutonium by sea have required extraordinary security arrangements. Even so, a 1988 Pentagon study stated that "...even if the most careful precautions are observed, no one could guarantee the safety of the cargo from a security incident, such as an attack on the vessel by small, fast craft, especially if armed with modern antiship missiles."[1] However, unless the attackers were able to board the ship and carry away the plutonium before it sank or before additional security forces arrived or could pursue them, this may not be a very credible diversion scenario. Similarly, scenarios to commandeer the ship and evade the inevitable pursuit do not seem very credible. Therefore, at least from a security standpoint, fears over Japanese shipments of plutonium may be exaggerated. Nevertheless, if such shipments become commonplace, the potential risk of such an attack may increase.[2]

1 "Transportation Alternatives for the Secure Transfer of Plutonium from Europe to Japan," *Sea Transportation Alternatives,* U.S. Dept. of Defense, Mar. 7,1988.

2 See, for example, David E. Sanger, "Japan's Plan to Import Plutonium Arouses Fear that Fuel Could Be Hijacked," *New York Times,* Nov. 25, 1991, p. D8.

Except for the few countries with unsafeguarded reprocessing facilities (Israel, India, and possibly North Korea[32]), obtaining plutonium for weapon purposes would require its diversion at the foreign reprocessing facility and subsequent illegal transfer to the target country, or diversion from safeguards within the country to which it had been returned (see box 4-C). Such steps would be legally risky and perhaps very costly to attempt in secret, but they remain a possibility.

MATERIAL LEAKAGE FROM FORMER SOVIET REPUBLICS

If security and control of the former Soviet nuclear weapon establishment breaks down, the diversion of nuclear materials maybe more likely than the smuggling of intact weapons. Weapon material can be shipped in much smaller and lighter quantities than can complete weapons, and in forms that (unlike weapons) are not discrete, countable units. Significant amounts of nuclear material could conceivably escape without detection by accounting procedures-specially at bulk-handling facilities. Indeed, numerous allegations that former Soviet weapon materials have been offered on the black market have already appeared in the press.[33] So far, the U.S. Central Intelligence Agency reports that it has not been able to verify *any* transfer of weapon-grade materials in significant quantities, and its director has testified that 'most reports of transfers appear to be scams, hoaxes, or exaggerations. ' However, it is impossible to be certain that *all are.*[34]

32 North Korea has suspended its announced intention to withdraw from the Nuclear Non-Proliferation Treaty and is therefore still bound by its safeguards agreement with the IAEA, but has not yet resolved its dispute with the IAEA concerning the conditions of this agreement. The IAEA has therefore been unable to confirm North Korea's adherence to safeguards.

33 See, for example, Marc Fisher, ''Germany Reports a Surge in Nuclear Smuggling Cases,' *Washington Post,* Oct. 10, 1992, p. A27.

34 Testimony of R. James Woolsey, Feb. 24, 1993, op. cit., footnote 15.

The reports of nuclear smuggling out of the former Soviet Union, even though most are probably hoaxes, illustrate an important new aspect of the proliferation problem. First, they add substantial amounts of ''noise' to the system, making it more difficult to distinguish real proliferation threats from false ones. Second, by their very existence, they demonstrate the willing complicity of supply-side middlemen with covert channels in the former Soviet Union, The potential for nuclear smuggling has thus become an important issue.

In addition to the threat of diversion of ex-Soviet weapon material from stockpiles that are nominally under Russian military control, other material might be available from civil nuclear facilities within Russia, or from active or mothballed facilities in other republics.[35] As an NPT nuclear-weapon state, Russia is not subject to mandatory safeguards at any of its nuclear facilities, and several of the former Soviet republics have not yet joined the NPT[36]

The issues presented by Russian plutonium from dismantled weapons are quite different from those surrounding Russian weapon HEU. The United States is negotiating the purchase of 500 tonnes of Russian HEU over the next 20 years for use in commercial power reactors. (The HEU would be blended down to LEU in Russia before the material was transferred.) No comparable purchases are envisioned for weapon-grade plutonium, making it possible that Russia would choose to recycle its excess plutonium as MOX in its own power reactors or to keep as many as 10,000 to 20,000 plutonium pits (the nuclear weapon cores that contain the fissile material) in long-term retrievable storage.[37] Both the plutonium and the HEU could conceivably end up in the wrong hands unless adequate measures are taken to regulate their transport, storage, and ultimate disposition. Procedures are required to minimize and safeguard stockpiles of both plutonium and HEU, to use them in commercial fuel or, in the case of plutonium, to dispose of it in safe and acceptable ways, all while taking into account strong economic pressures and potential political instability.

HEU FROM RESEARCH REACTORS

Over 100 of the approximately 325 total worldwide research and test reactors are fueled with highly enriched uranium (HEU enriched to more than 20 percent uranium-235), for which the total HEU inventory is about 4,000 kg. Most of this HEU inventory is in the form of 90 to 93 percent uranium-235. Thirty-six HEU-fueled research and test reactors are in the United States, some 2 dozen are in Russia and other former Soviet republics, and the remainder are located in about 34 additional countries. Approximately 40 of these foreign reactors (not including those in the former Soviet Union) are rated at over 1 MW(t), and many contain several kilograms of HEU fuel.[38]

The United States is one of the principal suppliers of research-reactor fuel, exporting 100 to 150 kg HEU annually. To reduce the proliferation risks posed by HEU reactors, the United States has developed and tested several types of compatible high-density LEU fuels that can be substituted for HEU fuels in research reactors. All but 3 of the ca. 40 foreign HEU-fueled research reactors larger than 1 MW(t) could be converted to LEU fuels developed so far, but only about 10

---

35 William C. Potter, Eve E. Cohen, and Edward V. Kayukov, *Nuclear Profiles of the Soviet Successor States, Monograph No. 1 (Monterey,* CA: Program for Nonproliferation Studies, Monterey Institute of International Studies, May 1993); and Oleg Bukharin, *The Threat of Nuclear Terrorism.*... op. cit., footnote 12, pp. 4-5.

36 As of November 1993, only Armenia, Azerbaijan, Belarus, Estonia, Latvia, Lithuania, Russia, and Uzbekistan had joined the NPT.

37 See U.S. Congress, Office of Technology Assessment, *Dismantling the Bomb and Managing the Nuclear* Materials, op. Cit., footnote 26,

38 Milton M. Hoenig, ' 'Eliminating Bomb-Grade Uranium Fuel from Research Reaetors," *Nuclear Control Institute,* January 1991, p. 3; and Oleg Bukharin, *The Threat of Nuclear Terrorism...*, op. cit., footnote 12, p. 5.

(a) During a U.N. inspection in October 1991, IAEA inspectors examine the bomb damage to the IRT-5000 research reactor at Al-Tuwaitha.

(b) The Tammuz-2 reactor was also damaged by coalition bombing during Operation Desert Storm. Both reactors had been fueled by highly enriched uranium.

have plans to do so. Only a handful of other research reactors have been converted so far. (Reactors operating at less than 1 MW(t) generally have lifetime cores, providing little incentive to convert.)39

Although all the HEU used in non-nuclear-weapon-state reactors is obtained from suppliers that require it to be placed under IAEA safeguards, a nation or terrorist group would have little difficulty in recovering HEU metal from fresh fuel if it were seized from storage at the reactor site or in transit.[40] Even if the fuel were lightly irradiated, e.g., for a few hours per week at less than 100 kW (e.g., in a typical university research reactor), the small quantities of radioactive fission products it would contain would not prevent recovery of the uranium, especially after waiting a few days or weeks for the fuel's activity to decay to lower levels.[41]

Most research-reactor fuel, however, has been irradiated for longer than this, making it much more radioactive and difficult to handle. Theft of such fuel (though likely to be regarded as a very serious incident), would also be an unlikely means of acquiring a nuclear *arsenal, since* quantities are limited in any one location and, in most reactors, are significantly less than what is needed for a weapon. Although crossing the nuclear threshold by obtaining material for even one bomb poses a significant danger, it is not as serious a threat as assembling a production line for making nuclear weapons in quantity. For these reasons, the proliferation concerns involving diversion or theft of HEU research-reactor fuel are legitimate, but limited in scale.[42]

Indigenous Production of Materials

The **alternative to stealing,** diverting, or purchasing weapon-grade nuclear materials is manu-

39 Hoenig, ' 'Eliminating Bomb-Grade Uranium Fuel. . .," ibid., p. 3; see also Armando Travelli, "The RERTR Program: A Status Report,'' Argonne National Laboratory, Oct. 2, 1992,

40 For instance, even before Iraq was discovered to have a massive nuclear weapon program, there was concern that it might have diverted for nuclear weapon use the 12,3 kg of 93% HEU originally supplied by France for its 40 MW(t) Osirak reactor or the 13.6 kg of Soviet-supplied 80% enriched fuel. (See footnote 5 in box 4-D.)

41 Hoenig, ' 'Eliminating Bomb Oracle Uranium Fuel. . .,'' op. cit., footnote 38, p. 3.

42 Research reactors can also be used to produce plutonium, however, which is also a concern. See below.

facturing them indigenously. Many different approaches to producing nuclear materials are available, depending on what nuclear materials a proliferant starts with, what access it has to dual-use or nuclear-specific technologies, and what cost it is willing to bear to acquire proscribed technologies on the black market. Various approaches also place specific demands on a proliferant's technology base, infrastructure, and expertise, and pose different operational difficulties and risks of detection once acquired.

International nonproliferation policies have made it quite difficult to use turn-key imported facilities to produce weapon-grade materials. The Nuclear Non-Proliferation Treaty prohibits NPT parties from exporting major nuclear facilities—especially those for uranium enrichment or reprocessing-unless they are placed under IAEA safeguards. (Those goods requiring the imposition of safeguards have been placed on a multilaterally agreed ''trigger list.") In April 1992, all 27 members of the Nuclear Suppliers Group (NSG) further agreed to require full-scope safeguards-the imposition of IAEA safeguards not only on the transferred facility but also on all other nuclear facilities in the recipient country—as condition of any significant new nuclear exports to nonweapon states. NSG countries also adopted stringent licensing and export policies for a new list of 65 categories of *dual-use* items (see app. 4-D). However, several nations experienced in nuclear technology-including Argentina, Brazil, China, India, and Ukraine-are not members of the NSG, though at least Argentina has stated that it would abide by the original 1977 NSG export guidelines.

Material production could involve obtaining LEU and enriching it further to produce HEU, or it could require creating the entire nuclear fuel cycle indigenously, starting with uranium ore and ending up with plutonium (see table 4-l).

ACQUISITION OF NATURAL URANIUM

Production of either weapon-grade uranium or plutonium starts with uranium ore, followed by a number of processing stages that are described below. As the materials approach weapon grade, their processing facilities become more specialized, and international controls on their use and shipment become more stringent.

Uranium ore, which is commonly mined along with other mineral-bearing ores and contains only about 1 part in 500 of uranium, is not subject to safeguards. Similarly, milling facilities that extract the uranium concentrate known as "yellowcake" (U_3O_8) from ore are not safeguarded. (The *amounts* of yellowcake exported or imported by NPT states having formal safeguards agreements in force must be reported to the IAEA, but such transfers are not verified by inspections. In the past, various countries have reportedly attempted to acquire yellowcake clandestinely.[43]) Mining and milling processes suitable for extracting uranium concentrate are standard in the mining industry. Many countries that are or had been of proliferation concern have large indigenous deposits of uranium-bearing ore and already operate mines and milling facilities.[44]

Yellowcake effectively becomes subject to safeguards inspections only after it is introduced into a declared conversion plant that produces a form of uranium suitable for further enrichment (e.g., uranium hexafluoride) or for fuel fabrication

43 For example, Israel is widely believed to have orchestrated the disappearance in November 1968 of 200 tom of yellowcake that was being shipped from Antwerp to Genoa (Spector, *Nuclear Ambitions*, op. cit., footnote 16, p. 155). Between 1978 and 1980, Pakistan is believed to have acquired from Libya quantities of up to 100 tons of yellowcake that Libya had originally purchased from Niger. (John J. Fialka, "West concerned by Signs of Libyan-Pakistan A-Effort, " *Washington Star*, *Nov. 25, 1979;* and Spector, *Nuclear Ambitions*, op. cit., footnote 16, p. 176.) Although Libya had been a member of the NPT since 1975, it was not required to report its imports or exports of yellowcake until it concluded a formal safeguards agreement with the IAEA in 1980.

44 See *Uranium Resources, Production, and Demand*, a Joint Report of the OECD Nuclear Energy Agency and the IAEA (Paris: OECD, 1986), and other references cited in Spector, *Nuclear Ambitions*, op. cit., footnote 16.

(e.g., oxide, metal, alloy, or carbide). Such further processing typically uses specialized facilities that would trigger the application of IAEA safeguards if imported; to evade safeguards at this stage, a proliferant would have to construct a clandestine conversion facility with uncontrolled goods. Doing so would add expense and effort but would probably not introduce particular roadblocks.[45]

PLUTONIUM PRODUCTION AND REPROCESSING FACILITIES

A key step in pursuing the plutonium route is obtaining a source of irradiated uranium, either by diverting spent fuel from a safeguarded reactor or by irradiating uranium in a dedicated plutonium-production reactor. The reactors most commonly used commercially, called "light-water reactors, ' are difficult to divert fuel from clandestinely, since their fuel rods are readily accounted for (if safeguarded), and since shutting such reactors down for refueling creates an observable event (even when unsafeguarded). Moreover, they require enriched uranium to operate, which is much more difficult to obtain outside of safeguards than is natural uranium.

Rather than divert fuel from a safeguarded reactor, a proliferant might build a dedicated plutonium-production reactor fueled by natural uranium. The section below discuses costs for two possibilities: a small (30 MW thermal output) reactor based on a widely available design that could produce sufficient plutonium for 1 or 2 weapons per year, and a larger (400 MW thermal) reactor that could produce some 10 to 20 weapons-worth of plutonium annually. Such production reactors would be based on reactor technologies better suited to plutonium production than is the light-water design, but these alternate technologies typically require specialized materials such as heavy water or ultra-pure graphite which, if imported, would trigger the imposition of safeguards.[46] AS is also discussed below, the construction and operation of a nuclear reactor produces a number of indicators or signatures that might reveal its existence (see section on monitoring).

The combination of a nuclear reactor and reprocessing plant offers a potentially less technologically advanced route to weapon-usable *material than* many methods of uranium enrichment. Israel and India, for instance, operate unsafeguarded reactors and reprocessing facilities that, in part, were built indigenously, and North Korea has built and operated similar facilities that were initially outside of safeguards.[47]

Extracting plutonium from spent fuel utilizes chemical processes that, in theory, have been within the grasp of most middle industrial powers for some time (see table 4-2). The principal difficulties in building a reprocessing plant stem from the intense radioactivity of the spent fuel to be reprocessed. Remote-handling equipment, radiation shielding, and other specialized equipment must be built and maintained to protect plant workers. Although most of the chemicals used in a reprocessing plant are available commercially, much of the needed equipment is export-controlled, and many countries would be unable to build such facilities without foreign technical assistance. Large facilities have notoriously taken a very long time to construct, and for technical as

45 Fuel fabrication and cladding, for example, might be done in a common metalworking shop.

46 Molecules of heavy water have their two hydrogen atoms replaced by deuterium atoms, an isotope of hydrogen having an extra neutron in the nucleus. Although present in small quantities in naturally occurring water, heavy water is a controlled nuclear-related material once concentrated. Heavy-water and ultra-pure graphite are effective neutron moderators having very low neutron absorption thus permitting reactors to operate on natural uranium; both materials are on the IAEA "trigger list' of nuclear goods that cannot be exported by an NPT-member state without the imposition of safeguards. However, it may be possible to manufacture such graphite indigenously or to obtain nonreactor-grade graphite commercially that could be used in reactors (possibly after additional purification) without triggering safeguards.

47 Spector, *Nuclear Ambitions*, op. cit., footnote 16, pp. 86, 139, 172 In the 1960s, however, India benefited from shared U.S. technology and Israel obtained significant technical assistance from France.

Table 4-2—Reprocessing Programs and Capability Outside the Declared Nuclear Weapon States

Country	Reprocessing facility	Dates of operation	Capacity (actual or projected) [t HM/yr][a]	Safeguards?
Japan	Tokai-mura	1981 -present		yes
	Rokkasho-mura	2005?	[800]	yes
Germany	Karlsruhe	1971-1990	35	yes
Belgium	Eurochemic-Mol	1966-1974	30	yes
Israel	Dimona	1966? -	[50-100]?	no
India	Trombay	1966-1974; [1983-present]?	30	no
	Tarapur	1982-present	100	partly
	Kalpakkam	1 993/94	[200]?	no
Pakistan	Chashma	construction ended 1978?	[100]	NA
	Rawalpindi	not operating?	[5]?	no
North Korea	Yongbyon	[1992]?	pilot-scale?	[yes][b]
Iraq	Tuwaitha	1989-1991 (destroyed)	lab-scale	(violation)
South Africa	Pelindaba	[1987-?]	pilot-scale?	yes[c]
Argentina	Ezeiza	suspended 1990	[5]	partly
Brazil	Resende	suspended 1980s	[3]	yes
South Korea	NA	abandoned 70s	NA	
Taiwan	NA	abandoned 70s	NA	

a Tonnes heavy metal per year. Items in [brackets] or with question marks represent estimates or substantial uncertainty, respectively.
b Although North Korea became a member of the NPT in 1985, its safeguards agreement with the IAEA was not signed until 1992, and the implementation of this agreement was still under negotiation as of November 1993.
c Prior to South Africa's joining the NPT in 1991, this facility was only under safeguards when safeguarded fuel was present. Since then, it has come under full-scope safeguards.

SOURCE: Adapted from David Albright, Frans Berkhout, and William Walker, *World Inventory of Plutonium* and *Highly Enriched* Uranium, 1992 (Oxford: Oxford University Press/SIPRI, 1993), p. 90; and Leonard S. Spector and Jacqueline R. Smith, *Nuclear Ambitions: The Spread of Nuclear Weapons, 1989-1990* (Boulder, CO: Westview Press, 1990).

well as economic and political reasons, even the smaller ones are sometimes abandoned before completion.[48] Furthermore, the IAEA and U.N. involvement and the ongoing negotiations with North Korea aimed at resolving the dispute over its nuclear facilities have demonstrated the kind of pressure that can be brought to bear on countries harboring suspect facilities when their existence is known.

France, the U. K., and Japan, which each operate commercial reprocessing facilities, are not current nuclear proliferation concerns.[49] France and the U.K. are already nuclear weapon states, and Japan, as a non-nuclear-weapon NPT

[48] For example, construction on a large reprocessing facility was begun in Pakistan in the late 1970s with French assistance, but may have been abandoned sometime following France's termination of its involvement in 1978. In 1990, Argentina also indefinitely suspended its work on building a small reprocessing plant at Ezeiza. See Spector, *Nuclear Ambitions*, op. cit., footnote 16, pp. 115, 239.

[49] India, on the other hand, operates a medium-size reprocessing facility at Tarapur that is not under full-time safeguards, thus allowing it the option of producing weapon materials free of international legal constraints if it so chose. Russia continues to operate three reprocessing plants, but in the past has not segregated civilian from military operation. States that once reprocessed civilian spent fuel but have discontinued doing so include Germany, Belgium, and the United States.

Under IAEA supervision in October 1991, Iraqi workers pour concrete into glove boxes at Al Tuwaitha to prevent their future use. Glove boxes are used to *protect workers from radioactive materials such as plutonium,*

member, has all its facilities under full-scope IAEA safeguards. Even so, material-accountancy at large spent-fuel reprocessing plants involves inherent uncertainties that are not necessarily less than an IAEA-defined significant quantity of nuclear material.

In addition, plutonium fuel-fabrication facilities are also now operating in France, the U.K., Japan, Belgium, and Germany, and another one may soon be constructed in Chelyabinsk, Russia. Plutonium and uranium recycling policies in these countries, however, are still undergoing revision and may not be finalized for some years (see table 4-3).

URANIUM ENRICHMENT TECHNOLOGIES

Table 4-4 compares various enrichment technologies according to several factors that a proliferant country would have to consider before choosing to pursue a particular enrichment method. (See app. 4-B for descriptions of these enrichment technologies.) In addition to various characteristics of each method, a proliferant's choice will depend strongly upon its own technical infrastructure, expertise, and access to foreign technical assistance. For instance, Argentina's experience in metallurgy was likely an important factor in its decision to pursue gaseous diffusion, and Pakistan's theft of Dutch centrifuge designs was undoubtable influential in its decision to pursue that approach.

Table 4-5 concentrates on technical attributes of each process, comparing various enrichment techniques in terms of efficiency and separation factor per stage (and thus the number of stages required to enrich uranium to, say, 90 percent U-235). Each *stage* of an enrichment plant takes an input source of uranium, or '' feed,' and produces two outputs: one with a greater concentration of uranium-235 than the feed (the "product"), and the other depleted in uranium-235 (the "tails"). The *separation factor* indicates how much enrichment each stage provides. (It is defined as the ratio of the relative isotopic abundance of uranium-235 in the product to that in the tails.) Some approaches, such as electromagnetic separation, achieve very high degrees of separation per stage, and very few stages are needed to obtain highly enriched uranium. Others, however, only marginally enrich the product in each stage, and up to thousands of stages are needed to obtain HEU.

For enrichment approaches in which each stage provides only marginal enrichment and thus many successive stages are required, the stages are connected into *cascades.* Each stage (usually consisting of many individual elements working in parallel) feeds its product to the stage operating at the next higher level of enrichment and its tails to the next lower.

Table 4-5 also gives estimates for the amount of electricity per unit enrichment capacity required for each approach, with enrichment capac-

Table 4-3-Plutonium and Uranium Recycle Policies in Europe and Japan

Country	Plutonium recycle	Reprocessed uranium recycle	LWR-MOX program
Belgium	Yes?	?	MOX fabricator. Plans to load two reactors with MOX, beginning mid- 1990s.
France	Yes	Yes[a]	MOX fabricator. First phase (eight reactors) to be loaded with MOX by 1993.16 reactors to be loaded by late 1990s,
Germany	Yes	Tested with MOX	MOX fabricator. Leader in MOX experience. 18 reactors to be loaded with MOX.[b]
Italy	No'	No	No operating reactors.
Japan	Yes	?	MOX fabricator. Demonstration program (two reactors) planned for 1994-1997. Commercial program due to start in 1995, rising to 12 LWRs loaded with MOX by 2003.
Netherlands	Yes[d]	No	MOX R&D at Dodewaard was suspended as of 1992.
Russia	Expected	Yes	Uranium separated from VVER-reactor fuel is recycled in graphite-moderated (RBMK) reactors.
Spain	No	No	No.
Switzerland	Yes	?	Has loaded two reactors with MOX.
United Kingdom	No	Yes	Plans to become a MOX fabricator,

a Official French policy is to recycle uranium recovered from rep recessed spent fuel, either by re-enriching it or by using it as the matrix for LWR-MOX fuel fabrication. However, the low price of natural uranium has meant that the Electricité de France has shown little practical interest in uranium recycle.
b As of 1992, only 10 reactors had been awarded licenses to load MOX fuel, and MOX had been loaded at 7 of them.
c A small MOX test program ran at Garigliano in the 1970s. Most Italian separated plutonium has been used to fuel France's fast breeder reactor, Superphénix.
d A small MOX test program ran at Dodewaard in the 197& and 1980s. Dutch separated plutonium has been used in the Superphenix and Kalkar fast reactor cares.

SOURCE: Frans Berkhout et al., "Disposition of Separated Plutonium," *Science & Global* Security, vol. 3, No. 1, 1992, p. 14.

ity measured in terms of 'separative work units, or SWUs.[50]

Most of the sensitive technologies and components used for uranium enrichment fall under strict export controls, both in the United States and abroad, and are therefore very difficult to obtain on the open market. Nevertheless, some have escaped these controls, mainly due to lax enforcement and variability of regulations among supplier countries. For example, security leaks in the URENCO consortium-a uranium enrichment enterprise established by the British, Ger-

50 SWUs measure the decrease in entropy, or conversely the increase in order, resulting when a given isotopic mixture is split into two mixtures of greater and lesser concentrations. (Combining two pure substances--say pure uranium-235 and pure uranium-238-results in a mixture that is more disordered than its original constituents. Reversing that process by separating an isotopic mixture into its constituent parts therefore increases its order.)

Although the exact formula relating the number of SWUS to the concentration of uranium-235 in the feed, product, and tails is complicated, a rough approximation for the SWUs needed to produce a given amount of 3% or higher enriched product from natural uranium (with typical tail depletions of about 0.3%) is about 120-200 times the number of kilograms uranium-235 contained in that product. The low end of this range applies to final enrichments from 3 to 5%, the high end for those from 20 to 97% (see Allan S. Krass et al., *Uranium Enrichment and Nuclear Weapon Proliferation* (London: Taylor & Francis, Ltd., 1983), pp. 96-98, esp. formulas 5.2 and 5.6). For example, producing 1 kg of 3%, 20%, or 90% enriched product from natural uranium (with 0.3% tails) would require 3.4, 38, and 193 SWUS (and 7.5, 50, and 225 kg of natural uranium), respectively.

Table 4-4-Relative Ease of Developing Various Enrichment Technologies for Weapon Programs

	Diff	Cent	Aero	Chem	EMIS	IC/PC	AVLIS	MLIS	LAP
Availability factors:									
Technology/know-how widespread	+	++	+/-	+1-	++		+1-		
Components attainable	+/-	+/-	+	+[a]	++		.		.
Operational factors:									
Convertible LEU to HEU		++	+	+	++	+	++?	+?	.
Minimal training required	+	+	+	+	+	-.	. .	-.	. .
Uses standard UF_6 feed	+	+						+	+
Low maintenance requirements	+	+	+	+	--		. .		
Detectability factors:									
Small plant size	+1-	+		+	+1-	+	+	+	-
Short equilibrium time	--	+		--	+	+	++	+	?
Low power consumption	--	+	. .	+1-	--	+	+?	+	+
Commercially justifiable		++		?	--	?	?	?	?
Overall proliferation concern:[b]	+/-	++	+/-	+	+	--		+/-	

KEY:
+/++ Indicate favorable/very favorable factor from the perspective of a potential proliferant.
-/- indicate unfavorable/very unfavorable factor.
? indicates insufficient information.

Diff - Gaseous diffusion
Cent = Gas centrifuge
Aero = Aerodynamic methods (Becker nozzle or Helikon processes)
Chem = Chemical exchange (Japanese Asahi or French Chemex processes)
EMIS = Electromagnetic Isotope Separation (e.g., calutrons)
IC = ion Cyclotron Resonance
PC - Plasma Centrifuge
AVLIS - Atomic Vapor Laser Isotope Separation
MLIS = Molecular Laser Isotope Separation
LAP = Laser-Assisted Process (e.g., Chemical Reaction by Isotopic Selective Laser Activation, or CRISLA)

a The ion-exchange resin developed and used in Japan by the Asahi Chemical Co. is proprietary and would be difficult to duplicate, even if samples could be obtained. However, a number of research programs around the world are developing fast equilibrium-time resins that might be useful for future chemical enrichment applications. it has also been reported that Ukraine produces an ion-exchange resin similar to that used in Japan's Asahi process (William C. Potter, Monterey Institute of International Studies, private communication, November 1992).

b Overall Proliferation concern should be taken only as a very rough indicator, since it is *strong/y country-dependent.* In arriving at this overall rating, "availability" and "operational" factors were each given twice the weight of the "detectability" factors, but for countries with an advanced technology base or skills suited to a particular technology, the relative weighting might be very different.

SOURCE: Allan S, Krass et al., *Uranium Enrichment and Nuclear Weapon Proliferation* (London: Taylor & Frands, Ltd., 1983), p. 19; Marvin Miller and George Rathjens, "Advanced Technologies and Nuclear Proliferation," in Robert H. Bruce, ad., *Nuclear Proliferation: South Asia and the Middle East,* Monograph No. 2 (Perth, Australia: Indian Ocean Center for Peace Studies, 1992), pp. 107-123; and OTA (see app. 4-B on enrichment technologies).

Table 4-5—Efficiency of Uranium Enrichment Technologies[a]

	Separation factor or enrichment factor[b]	No. of stages for 90% HEU[c]	kWh/SWU	kW for 4,000 SWU/yr
Gaseous diffusion	1.004-1.0045	3,500-4,000	2,500	1,200
Gas centrifuge	1.2-1 .5[d]	40-90	100-200	50-100
Aerodynamic				
Helikon/UCOR	1.030	540	4,000	2,000
Becker nozzle	1.015	1100	3,600	1,800
Chemical				
French Chemex	1.002-1.003	5,000-8,000'	600	300
Japanese Asahi	1.001-1.0013	12,000-1 6,000'	150	75
Electromagnetic[b]				
EMIS (calutron)	20-40	2-3	20,000 -30,000[f]	10,000-15,000
ion cyclotron resonance/ Plasma centrifuge	- [3-10]	[4-8]	[200-600]	[100-300]
Laser processes				
AVLIS	- [5-1 5]	[a few]	[100-200]	[50-100]
MLIS	- [3-1 o?]	[under 10?]	[200-250]	[100-125]
LAP (CRISLA)	~` [1.5][g]	- [20]	[tens?]	[low]

a Estimates in [brackets] are uncertain and may not be achievable on an industrial scale.

b For electromagnetic and laser processes, estimates are for the *enrichment* factor, not the separation factor. "Separation factor" is defined as the ratio of the relative (^{235}U-to-^{238}U) enrichment of the product to that of the tails in any one stage of a cascade, and is the figure given for diffusion, centrifuge, aerodynamic and chemical processes. "Enrichment factor" is the ratio of relative enrichment of the product to that of the *feed*, which is more relevant to processes whose separation per stage is high enough that a many-stage cascade is not required, and in which the "cut" (the ratio of the total amount of material in the product to that in the tails) is therefore not as relevant. The separation factor for a given process is always larger than its enrichment factor, but only slightly larger when the cut is much less than 50%, as it may be in some laser processes.

c *Assumes* tails with 0.3% ^{235}U content.

d The given range applies t. modern centrifuges and is dependent on their length, rotational speed, and other factors. The earliest centrifuges operated at subcritical peripheral speeds of 250 m/see and had separation factors of only 1.026. See Manson Benedict and Thomas H. Pig ford, *Nuclear Chemical Engineering, 2nd ed. (New York,* NY: McGraw-Hill, 1989), chapter 12.

e For chemical processes, a single physical item (e.g., an ion exchanger or pulse column) can contain tens or hundreds of effective "stages, " so that these large numbers can be misleading.

f This figure is sometimes given as 3,000-4,000 (e.g., see Krass et al., below, p. 189), which would apply only to significantly improved calutrons that used multiple beams, permanent magnets, or other refinements. The figure given in the table is based on U.S. "Alpha" machines *used* during the Manhattan Project, which produced *only* about 1/3 gram uranium-235 per machine per day in about a 20% enriched product, and used more than 50kW per machine to power the electromagnets, pumps, and ion beams.

9 Estimate from Marvin Miller; derived from prelim inary 1986 data of Isotope Technology, a small west-coast firm promoting the CRISLA process.

SOURCE: Adapted by OTA from U.S. Department of Energy, *Nuclear Proliferation and Civilian Nuclear Power, Report of the Nonproliferation Alternative Systems Assessment Program* (NASAP), "Volume II: Proliferation Resistance," DOE/NE-0001/2, June 1980, p. 3-7; Allan S. Krass et al., *Uranium Enrichment and Nuclear Weapon Proliferation* (London: Taylor & Francis, Ltd., 1983), p. 188; and Marvin Miller, "Atomic Vapor Laser isotope Separation," FY1989 Arms Control Impact Statements, (Washington, DC: U.S. Government Printing Office, April 1988), p. 142.

man, and Dutch governments-have contributed to the proliferation of its centrifuge design technology.

Some components of very old technologies, such as electromagnetic isotope separators (EMIS, also known as "calutrons' '), and of very new technologies-some of which have still not been developed to a commercial scale by even the most advanced industrialized countries-have not been subject to export controls.[51] For example, magnets and beam sources for EMIS, and some lasers that could be used for laser isotope-separation techniques, have such widespread commercial applications that they have not been controlled in the past.[52]

Although gaseous diffusion dominated Western commercial enrichment for over three decades, it is now being overtaken by gas centrifuge technology. Neither technique has yet been used outside the five acknowledged nuclear powers to produce HEU on a large scale. However, the proliferation potential of centrifuges has won considerable attention both because of Iraq's pursuit of the technology before the Gulf War and because of Pakistan's success at building its own modem gas centrifuge plant with the help of blueprints and purchase orders stolen from the Dutch factory of the URENCO consortium.[53]

Detailed information on older centrifuge technology, in fact, is available in published documents.[54] However, these comparatively rudimentary designs are at least 25 times less efficient in terms of energy use and separation capacity than modem designs, whose manufacturing processes, design parameters, and operating characteristics remain classified. Older designs therefore cannot lead to facilities nearly as compact and efficient as those using modem technology. However, it is now becoming known that the former Soviet Union began developing gas-centrifuge technology on a massive scale in the 1950s and has advanced to fifth-generation designs. Russia continues to operate four major gas-centrifuge enrichment plants-though since 1987 these have only produced LEU for reactors—with a total capacity of about 10 million "separative work units" (SWUs), about half the world's total for this technology .55

Conversion of an existing facility

Large commercial enrichment facilities producing LEU for nuclear power plants, if reconfigured for higher enrichments, would

---

51 In 1961, the U.S. declassified the technology fo, electromagnetic and aerodynamic enrichment techniques, and for gaseous diffusion except for its diffusion barriers and pump seals. Germany found little difficulty in sharing the technology it had developed for the Becker nozzle aerodynamic process with South Africa, which in turn went on to develop on an industrial scale a different version of the process called Helikon, or ''stationary-wall" centrifuges. Although designs are also available in the open literature for early gas centrifuges, *modern* centrifuge technology remains classified both in the U.S. and by the URENCO consortium.

52 Note, however, that the new Nuclear Suppliers Guidelines for dual-use items, once implemented, will tighten export controls on many of these technologies (see app. 4-D).

53 Shyam Bhatia, Nuclear Rivals in *the Middle East* (London: Routledge, 1988), p. 8; James Adams, *Engines of War: Merchants of Death and the New Arms Race (New York, NY:* Atlantic Monthly Press, 1990), pp. 200-203; and Spector, *Nuclear Ambitions*, op. cit., footnote 16, pp. 90,97. Illicit efforts by proliferant states to obtain goods and technology have continued, as witnessed by the July 7, 1992 conviction in Philadelphia of Pakistani General Inam al-Haq for conspiring to illegally export maraging steel-350 (a material needed to construct gas centrifuges).

54 See, for example, Gernot Zippe, *The Development of Short-bowl Ultracentrifuges*, University of Virginia Report No. EP-4420-101-60U, submitted to Physics Branch, division of Research, U.S. Atomic Energy Commission, Washington, DC, July 1960, referenced in Krass et al., *Uranium Enrichment. . . .* op. cit., footnote 50.

55 See Mark Hibbs, *Nuclear Fuel*, Oct. *26,* 1992, *p. 3;* Oleg Bukharin , *The Threat of Nuclear Terrorism. . . .* op cit., footnote 12, August 1992, p. 4; and David Albright, Frans Berkhout, and William Walker, *World Inventory of Plutonium and Highly Enriched Uranium, 1992* (Oxford: Oxford University Press/SIPRI, 1993), pp. 54-56. According to these sources, all Russian centrifuge plants employ subcritical, aluminum-rotor centrifuges with annual throughput believed to be only around 5 SWU per machine,

have the enrichment capacity to make HEU for tens of weapons annually from the same amount of uranium source material required each year to fuel just one commercial-size nuclear power plant. Furthermore, each such enrichment facility typically supplies fuel for many tens of power reactors annually.[56]

If the enrichment technology is capable of doing so, upgrading 3 percent enriched uranium to 90 percent enriched uranium requires only about as much energy and enrichment effort as was required to enrich the 3 percent uranium in the first place. Although a cascade to enrich a *small* amount of LEU to weapon-grade levels would require several times as many *stages* as an LEU facility, each stage could be built with many fewer or much smaller elements, and it would cost only a fraction that of a large enrichment facility. Therefore, if they could avoid detection by safeguards (which would be difficult), those few countries already possessing commercial enrichment facilities could easily produce substantial amounts of nuclear weapon material by reconnecting part of a facility to produce 90 percent enriched material, by secretly adding additional enrichment stages, or by diverting some 3 percent enriched material to another (clandestine) facility .57

A covert facility fed by a small amount of diverted LEU, in theory, could be quite small and difficult to detect, although safeguards are designed to detect the diversion of the LEU. (See the following section.) The difficulty of reconfiguring an existing facility without detection, as opposed to building a new one, however, depends upon the type of enrichment technology used. Converting a large gaseous diffusion or chemical-exchange plant without detection from low to higher enrichments would be extremely difficult. Doing so would require either a complex reconnection of cascade elements, the addition of thousands of additional stages, or the reintroduction of enriched material into the original feed point.[58] Given the size of commercial facilities, it could take from months to over a year to re-establish steady-state plant operation after such a change, during which the change would almost certainly be detected.

Centrifuge cascades, on the other hand, can relatively easily be made to produce higher enrichments-either by adjusting the feed rates, by reintroducing higher enriched material into the feed, or by reconfiguring the cascade itself.[59] Since centrifuge-cascade equilibrium times are on the order of minutes to tens of minutes, such a change in enrichment levels could be accom-

56 That a commercial nuclear reactor requires far more fissile material than a nuclear weapon can be seen by comparing their energy outputs. A 1,000 MW(e) nuclear power plant, which generates heat through fission at a rate of about 3,000 MW, releases the energy equivalent of about 60 kilotons of TNT each day.

Alternatively, starting with natural uranium, less than 5,000 SWUs of enrichment effort are needed to produce an IAEA significant quantity (25 kg) of highly enriched (90 percent) uranium. In contrast, over 100,OOO SWUs are required to produce the approximately 30 tons of 3% enriched uranium consumed each year in a large commercial reactor, and commercial enrichment facilities have capacities of millions of SWUs per year.

57 The only non-nuclear-weapon states actively involved in commercial enrichment for nuclear power are (see table 4-7) Japan, South Africa, and those countries participating in two consortia: URENCO and Eurodif. URENCO, established in 1971 by the U. K., W. Germany, and the Netherlands, operates several large centrifuge-based enrichment plants, Eurodif, a private commercial collaboration involving France, Italy, Belgium, Spain, and Iran that began soon thereafter, operates a large gaseous diffusion plant (10.8 million SWU/yr) at Tricastin in France. (Iran has been excluded from active participation since the 1979 revolution.)

58 Especially for chemical-enrichment methods, which employ liquid phases, reconfiguration fOr HEU could also require Smaller elements to avoid the possibility of criticality accidents.

59 Adjusting the feed rates can increase the enrichment of the product up to some maximum for a given cascade, called the "total reflux' enrichment level. If normal operation of a given cascade produces ^{235}U enriched product, then operating near total reflux could produce around 12% enrichments. Krass et al., *Uranium Enrichment*. . . . op. cit., footnote 50, p. 116. MLIS and the South African Helikon techniques might also offer advantages for producing HEU, but MLIS is still in the developmental stages, and the Helikon method currently utilizes an inflexible architecture. (See table 4-4 and table 4-5.)

Part of a gas-centrifuge cascade operated by Japan's Power Reactor and Nuclear Fuel Development Corporation (PNC). As required by the NPT all of Japan's nuclear facilities come under IAEA safeguards and are regularly inspected.

plished much more rapidly than for gaseous diffusion plants, whose: equilibrium times are weeks to months.

It is unlikely that operators of existing safeguarded centrifuge facilities would reconfigure or operate them clandestinely to produce HEU. Nevertheless, such a reconfiguration or modified operation is certainly possible and might even elude detection if them were a several-month period between safeguards inspections and if the alteration could somehow be made to look to the plant's containment and surveillance system like routine maintenance. Any such reconfiguration would require the collusion of many plant operators to keep it secret, however, providing a further deterrent.[60]

Building a dedicated facility

Table 4-6 lists the specialized requirements for the different enrichment approaches that could be taken by a potential proliferant who wished to build a dedicated uranium enrichment facility, indicating which are currently subject to export controls. Table 4-7 presents the status of each of the enrichment approaches in a number of countries. Many states have conducted R&D into a number of different approaches, with 10 non-nuclear-weapons states apparently having built pilot plants or production capability utilizing at least one of these enrichment methods. In India, Pakistan, and Iraq, those facilities have not been safeguarded, and in Brazil, Argentina, and South Africa, they have only recently been placed under safeguards.

The smallest, most easily hidden enrichment facilities would be based on energy-efficient processes that achieved high levels of enrichment in just a few stages. For example, laser and possibly plasma separation processes would be quite valuable to a proliferant state seeking a covert enrichment facility. However, energy efficiency and high separation per stage are usually directly related to technical complexity, and these advanced techniques will probably remain relatively inaccessible to developing countries for some time. Despite more than two decades of development work on these techniques, the most technologically advanced countries in the world have only recently taken laser separation techniques beyond the laboratory-scale demonstration stage.[61]

Aerodynamic methods such as the Becker Nozzle and Helikon process (see app. 4-B) have higher separation factors than gaseous diffusion, enabling them to reach high enrichments with fewer stages and smaller facilities. With no moving parts other than the compressors and pumps, they are operationally less complex than

---

60 Moreover, as a result of the early 1980s Hexapartite Safeguards Project addressing safeguards fOr centrifuge enrichment facilities, countries operating the principal centrifuge facilities in Europe and Japan have agreed to the principle of limited frequency unannounced access (LFUA) as one way of further reducing the possibility of any such reconfiguration. The Hexapartite project involved Australia, Germany, Japan, the Netherlands, the United States, and the United Kingdom, as well as the IAEA and Euratom.

61 South Africa's Atomic Energy Corp., Ltd. plans to test a prototype molecular-laser-isotope-separation (MLIS) uranium enrichment-unit sometime in 1994, Note that this is in contrast to the AVLIS process currently being developed in the U. S., France, and the U.K. France announced in April 1992 that it had successfully produced 10 grams of low-enriched uranium using laser enrichment.

Table 4-6-Special Requirements for Uranium Enrichment Technologies

	Feed Material	Critical Equipment/Technology"
Gaseous diffusion	UF_6 gas	UF_6 processing equipment (corrosion-resistant)"; diffusion barrier"; specialized compressors/pumps/seals*; large heat exchangers.
Gas centrifuge	UF_6 gas	All components": maraging steel (or other high strength-to-weight materials); endcaps; rotors; bellows; center post tubes; specialized ring magnets, magnetic suspension assemblies, and bottom bearings; scoops; baffles; outer casing; drive systems such as inverters; desublimers; high temperature furnaces; UF_6 processing equipment (corrosion-resistant). Also: vacuum/molecular diffusion pumps.
Aerodynamic	4% UF_6 plus 96% H_2 (mixture)	UF_6 processing equipment (corrosion-resistant)"; jet-nozzle units' for Becker process, or vortex unit* for Helikon process (which uses a *2%/98%* gas mixture); compressors/pumps/seals (corrosion-resistant)".
Chemical	U compounds	Proprietary ion-exchange resin" and exchange catalysts* (for Asahi process), or organic solvents and avoidance of catalytic elements (for Chemex process).
EM IS (calutron)	UCl_4[b]	Large electromagnets; high-voltage power equipment; stable, high-current ion source; collectors; vacuum/molecular diffusion pumps; $UC1_4$ processing equipment; and uranium recycling plant.
Ion cyclotron	U metal	Superconducting magnets; large solenoids; ion source; liquid helium; radiofrequency power supplies.
Plasma centrifuge	U metal	(Same as ion cyclotron method, but excluding radiofrequency power supplies)
AVLIS	U metal	High-power, pulsed dye laser; copper-vapor laser; vacuum pump; uranium vaporization equipment (such as electron-beam heater); high-voltage collector power supply; refractory materials.
MLIS/LAP (CRISLA)	UF_6 gas	High-power pulsed $C0_2$ laser; CF_4, CO, or excimer lasers (16 mm I R and/or UV); UF_6 carrier-gas mixture; UF_6 processing equipment (corrosion-resistant)".
Thermal diffusion	liquid UF_6	UF_6 processing equipment (corrosion-resistant)".

a Those items marked with asterisks (*) have been regulated by export controls for many years. Many of the remaining items (subject to certain threshold specifications) will come under the new NSG dual-use export-control guidelines, once implemented by NSG countries (see app. 4-D). Note, however, that while such controls may impose significant barriers to acquisition, they do not make it impossible.

b Higher efficiency liquid metal ion sources might also be used. See V.E. Krohn, and G.R. Ringo, "Ion Sources of High Brightness Using Liquid Metal," *Appl. Phys.* Letters, vol. 27 (1975), p. 479; and Oswald F. Schuette, "Electromagnetic Separation of Isotopes," U.S. Congress, Office of Technology Assessment, *Nuclear Proliferation and Safeguards,* OTA-E-48 (Washington DC: U.S. Government Printing Office, June 1977), app. vol. 2, Part 2-VI-c, pp. 93-108,

SOURCE: Adapted by OTA from Sean Tyson, "Uranium Enrichment Technologies: Proliferation Implications," *Eye on Supply* (Monterey, CA: Monterey Institute for International Studies), No. 5, fall 1991, pp. 77-86,

Table 4-7-Status of Uranium Enrichment Technologies by Country[a]

	Diff	Cent	Aero[b]	Chem[c]	EMIS	IC	PC	LIS	AVLIS	MLIS	LAP
Declared nuclear weapon states:											
Us.	3	2	1	1	3	1	1		2	1	1
Russia	3	3		1	2				1		
France	3	1		2		1			1		
U.K.	3	3							1		
China	3	2		1	1						1
Nonnuclear-weapon states under safeguards with at least pilot-scale enrichment facilities:											
Argentina	2							1			
Brazil		2	2	1					1		
Germany	2	3	2						1	1	
Italy	2	1						1			
Japan	1	3		2					1	1	1
Netherlands	2	3							1		
South Africa		1	3							1	
Countries outside the NPT or otherwise of proliferation concern:											
India		2						1			
Iran	1				1			1			
Iraq	1	1	1	1	2						
Israel		1									
Pakistan		2									
NPT parties (under safeguards) with only R&D-level enrichment programs:											
Australia		1		1			1	1			
Belgium	1							1			
Canada										1	
South Korea								1			
Romania								1			
Spain	1							1			

a Entries indicate the highest level of development achieved by a given country baaed on unclassified sources. Some processes may have been discontinued by some countries.

b South Africa has developed the Helikon aerodynamic process to industrial scale; Germany, Brazil, and the United States have focused on the Backer nozzle.

c Japan and France have developed the Asahi ion-exchange and Chemex solvent-extraction chemical processes, respectively. The specifics of other countries' chemical-enrichment research programs are not known.

KEY:

1 = R&D
2- Pilot Plant: facility with enrichment capacity of leas than 100,000 SWU/yr.
3 = Industrial Capability: facility with capacity of 100,000 SWU/yr or more.
LIS = Laser isotope separation techniques, general (AVLIS, MLIS, or LAP) (See key to table 4-4 for other abbreviations.)

SOURCE: Adapted by OTAfrom David Albright, Frans Berkhout, and William Walker, *World Inventory of Plutonium and Highly Enriched Uranium, 7992*, (Oxford: Oxford University Press/SIPRI, 1993); Sean Tyson, "Uranium Enrichment Technologies: Proliferation Implications," *Eye on Supply* (Monterey, CA: Monterey Institute for International Studies), No. 5, fall 1991, pp. 87-88; Allan S. Krass et al., *Uranium Enrichment and Nuclear Weapon Proliferation* (London: Taylor & Frands, Ltd., 1983), p. 34.

centrifuges or laser processes.[62] Though not as energy efficient as centrifuges, aerodynamic methods can significantly enhance their production rates by using low-enriched uranium feed and can be used to produce very high enrichments.[63] They may therefore be a proliferation concern. However, complex small-scale manufacturing technology is required to fabricate critical aerodynamic components for the Becker nozzle technology, and the Helikon process is proprietary. Therefore, countries without very sophisticated technical capabilities would have to import such components (in violation of export controls).

Although key aspects are proprietary, chemical separation techniques such as the Japanese-developed ion-resin process and the French solvent extraction method are based on conventional chemical-engineering technology that in general is available to a great many countries around the world (see ch. 2). This enrichment approach could therefore prove difficult to control if the specific processes and materials involved were reproduced by a proliferant state.

Gaseous diffusion was the primary enrichment technique used by each of the five acknowledged nuclear powers. Classification by the United States of diffusion-barrier and compressor technology thus was not able to prevent its independent development by the other nuclear weapon states, even as early as the 1950s and 1960s.[64] Since then, however, the only other country that appears to have had some success at developing gaseous diffusion on its own is Argentina.[65] Since considerable engineering and materials expertise are required to design barriers and large corrosion-resistant compressors, the less-industrially advanced countries would still find it difficult to construct gaseous diffusion facilities.[66] Moreover, diffusion facilities are large and energy inefficient, making them virtually impossible to hide from detection on a commercial scale.

FROM NUCLEAR MATERIALS TO NUCLEAR WEAPONS

| Knowledge and Expertise

Although successfully designing a nuclear explosive device requires individuals with expertise in metallurgy, chemistry, physics, electronics, and explosives, the required technology dates back to the 1940s, and the basic concepts of nuclear bombs have been widely known for some time. Much of the relevant physics for a workable design is available in published sources. As the Iraqis and others have discovered, many unclassified or declassified documents can also be obtained that make designing a weapon considerably easier than it was for the first nuclear powers (see box 4-D).[67] The first gun-type weapon ever

62 The Helikon process was largely developed internally in South Africa after it purchased rights to the related Becker Nozzle technology from Germany. Brazil also invested in the Becker technology in the late 70s. See Spector, *Nuclear Ambitions,* op. **cit., footnote 16,** pp. 243, 270.

62 The Helikon process was largely developed internally in South Africa after it purchased rights to the related Becker Nozzle technology from Germany. Brazil also invested in the Becker technology in the late 70s. See Spector, *Nuclear Ambitions,* op. cit., **footnote 16,** pp. 243, 270.

63 Electromagnetic isotope separation also has these three attributes.

64 See Albright *et al., World Inventory...* op. cit., footnote 55, pp. 49-66.

65 Ibid., pp. 180-181.

66 Iraq, for instance, reportedly worked on gaseous diffusion for 6 years before abandoning it in favor of other methods. Jay C. Davis and David Kay, "Iraq's Secret Nuclear Weapon Program," *Physics Today,* July 1992, p. 22.

67 For instance, many basic physical principles of nuclear weapons (though not the implosion concept) are discussed in Robert Serber, *The Los Alamos Primer: First Lectures on How to Build an Atomic Bomb* (Berkeley, CA: Univ. of California Press, 1992). Serber's lectures were first given at Los Alamos at the start of the Manhattan Project in April 1943. Lecture notes were transcribed at the time and then declassified in 1965. The Iraqis legally obtained copies of many such documents from the West, such as declassified documents on lithium-6, a material useful for more advanced nuclear weapons. David Kay, head of several IAEA nuclear inspections in Iraq, private communication, Jan. 8, 1992.

Box 4-D-Iraq's Design Effort and Enrichment Approaches

Before the Gulf War, Iraqi scientists had progressed through several design iterations for a fission weapon based on an implosion design (one that is much more difficult to develop than the alternative, gun-type design-see app. 4-A). Still at the early stages of completing a design, they had successfully overcome some but certainly not all of the obstacles to a workable device.[1] Using HEU, a completed device based on the latest Iraqi design reportedly might have weighed from about a tonne to somewhat more than a tonne.[2] The Iraqis also possessed flash x-ray photography equipment and high-speed streak cameras? both useful in the R&D phase for studying the timing and compression achieved by a nuclear implosion design.

How close Iraq was to completing a bomb is still open to debate. At the request of the IAEA, a group of nuclear weapon designers from the United States, Britain, France, and Russia met in April 1992 to assess the progress of Iraq's nuclear program prior to the Persian Gulf War, based on documents that had been obtained through subsequent inspections. These designers reportedly concluded that bottlenecks in the program could have delayed completion of a working bomb for at least 3 years, assuming Iraq had continued its multifaceted strategy and design approach.[4] However, several experts familiar with the inspections believe that Iraq could also probably

1 See Peter Zimmerman, "Iraq's Nuclear Achievements: Components, Sources, and Stature," Congressional Research Service report 93-323F, Feb. 18, 1993, pp. 18-22 and esp. app. 4-B, which reprints the *Al-Atheer Plant Progress Report for the Period 1 January 1990 to 31 May 7990,* Annex to the Sixth Inspection Report, U.N. Security Council S/23122, Oct. 8, 1991 (English), app. 4-B, pp. 23-24. Al Atheer was the principal site for weaponization research, development, and experimentation, similar to some of the roles played by Los Atamos during the Manhattan Project. The sixth inspection included the famous incident in which inspectors were detained for 4 days in a parking lot in downtown Baghdad near Petrochemical-3 (PC-3) headquarters.

2 See, for example, Zimmerman, op. at., footnote 1, p. 19; and Colin Norman, "Iraq's Bomb Program: A Smoking Gun Emerges," *Science, vol.* 254, Nov. 1, 1991, pp. 644-645.

3 David Kay, head of several IAEA nuclear inspections in Iraq, private communication, Dec. 1,1992. See also *Al-Atheer Plant Progress Report for the Period 1 January 1990 to 31 May 1990,* op. dt., footnote 2, pp. 23-24.

4 Paul Lewis, "U.N. Experts *Now* Say Baghdad Was Far From Making an A-Bomb Before Gulf War," *New York Times,* May 20,1992, p. A6. See also, David Atbright and Mark Hibbs, "Iraq's Quest for the Nuclear Grail: What Can We Learn?," *Arms Control Today,* vol. 22, No. 6 (July/Aug 1992), p. 7.

designed (the Hiroshima weapon), in fact, was based on such a sure--fire technique that no nuclear test was deemed necessary before it was used in warfare. (See app. 4-A for discussion of nuclear weapon designs.)

Nevertheless, knowledge must be supplemented by industrial infrastructure and the resources to carry a nuclear weapon program to completion. The technologies for building cars and propeller-driven airplanes date back to early in this century, but many countries still cannot build them indigenously.

The following section discusses some of the key areas of technical expertise required to construct weapons once the materials have been acquired.

COMPUTER SIMULATION AND DESIGN CODES

High-performance computers are not now, and never were, an essential technology for designing fairly sophisticated nuclear weapons. Various types of weapon designs were developed by the United States (as well as perhaps each of the other declared nuclear powers) without *any* kind of electronic computer.[68]

68 With only very primitive computers, Chinese designers reportedly studied 1,000 physical prototypes of the bomb before designing their first nuclear weapon. John W. Lewis and Xue Litai, *China Builds the Bomb* (Stanford, CA: Stanford University Press, 1988), p. 155.

have produced a workable device in as little as 6 to 24 months, had they decided to seize foreign-supplied HEU from under safeguards and focus their efforts on a crash program to produce a device in the shortest possible amount of time.[5]

In addition to extensive development of the electromagnetic isotope separation technique (EM IS, also called calutrons) and preliminary work on centrifuge enrichment technology and materials acquisition,[6] Iraq had also been pursuing chemical enrichment including both the ion-resin process developed by the Japanese and the liquid-liquid solvent extraction process developed by the French (see app. 4-B). At the time of the Gulf War, most Western analysts-with the notable exception of the French-believed that the chemical enrichment facility at Tuwaitha "Building 90" was not yet operable. Subsequent inspections by the IAEA, under auspices of the U.N. Security Council Resolution 687, found lab-scale experiments in chemical enrichment, but no evidence of success or any plans for a production plant. Since the French technology is both proprietary and subject to export controls, the Iraqis reportedly resorted to clever negotiation tactics to garner considerable amounts of design information on the process, ostensibly with the goal of licensing the technology at some point in the future. Their techniques reportedly included pressing for more and more technical details during a contract negotiation and then breaking off discussions just before closing a deal.[7]

5 In April 1991, Iraq's inventory of safeguarded highly enriched uranium included *unirradiated* fuel in the amounts of 13.6 kg of Soviet-supplied 80%-enriched HEU plus under 0.5 kg (out of the original 12.3 kg) of French-supplied 93% HEU; plus *partially irradiated* fuel in the amounts of 3.6 kg of 80% and 11.8 kg of 93%. Additional 80%-enriched HEU was listed as *irradiated* (fissile material would have been difficult to extract quickly from the irradiated fuel). Johan Molander, U.N. Special Commission, quoted in "Iraq's Bomb Program: A Smoking Gun Emerges," op. cit., footnote 2, p. 254.

6 These aspects of the Iraqi program have all subsequently been described in some depth in published articles and reports. See, for example, Zimmerman, "Iraq's Nuclear Achievements. . .," op. cit., footnote 1.

7 David Kay, presentation at the National Institute of Standards and Technology (NIST), Gaithersburg, MD, May 15, 1992.

Moreover, most of the U.S. nuclear weapons developed through the mid- 1970s were designed with computers no more capable than a typical 1990 engineering workstation—i.e., 1,000 to 100,000 times less powerful than modem high-performance computers, which now perform well in excess of 1,000 MFLOPS (million floating-point operations per second);[69] these weapons included high-efficiency primaries and the first thermonuclear weapon (1950-55); small-diameter primaries and nuclear artillery (1955 - 60); small strategic warheads (1960-65); the warhead for the Spartan antiballistic missile (1965-70); and weapons with tailored outputs (1970-75).[70] Of course, U.S. designers had the benefit of an extensive series of nuclear tests, which allowed them to validate both the weapons themselves and the computer programs that helped design them.[71]

Records obtained during the sixth IAEA inspection in Iraq show that the Iraqis had developed or acquired a number of computer codes for

69 A typical "supercomputer" of the mid- 1980s, such as the CRAY X-MP, had a speed of about 100 MFLOPS. Jack Worlton, Laboratory Fellow, Los Alamos National Laboratory, "Some Myths about High-Performance Computers and Their Role in the Design of Nuclear Weapons," Worlton & Associates, Technical Report No. 32, June 22, 1990.

70 U.S. Department of Energy, "The Need for Supercomputers in Nuclear Weapons Design," January 1986 (declassified), as cited in Worlton, ibid.

71 Advanced Computation] power in the United States has also greatly facilitated miniaturizing nuclear weapons (i.e., achieving higher yield-to-weight ratios) and minimizing the amount of nuclear material they use. Moreover, it has promoted the development of 'safer' (less likely to detonate or disperse plutonium accidentally) and "cleaner" (for example, thermonuclear) weapons, and weapons that are designed to be reliable after being deployed for several decades.

use in their nuclear weapon design effort. These codes, found by IAEA inspectors, had been running on IBM PS/2 desktop computers;[72] such machines are capable of assisting with the design of first-generation nuclear weapons.

Since minicomputers, professional workstations, and other advanced computers roughly double in performance every 1 to 2 years, many types of computer become available worldwide not long after they are introduced, as they fall behind the rapidly advancing state of the art. Companies not subject to U.S.-style export controls—for example, in Israel, Brazil, India, and Bulgaria-are now developing and assembling indigenous high-perform ance computers comparable to or exceeding the best U.S. computers of just 5 or 6 years ago. A proliferant could also increase his computational power without violating export controls by installing accelerator boards for low-end to mid-range computers or by dedicating a relatively high-level machine (which is usually shared by many users simultaneously) to a single design effort.[73]

Therefore, top-of-the-line computers and numerical codes are certainly not a prerequisite to a successful nuclear weapon program, though their import may serve as an *indicator* of such and thereby provide valuable intelligence information. Given the utility of widely available computers to a weapon designer, even very strict export controls on top-model computers would probably do little to slow the development of a first-generation weapon program. Computational power would be relatively more important for programs pursuing advanced nuclear weapons, including thermonuclear ones.

NUCLEAR TESTING AND WEAPON FABRICATION

Although extensive testing of the implosion system and other weapon components would normally be essential before settling on a nuclear implosion design, *nuclear* testing (at full or nearly full yield) would not be required to field fission weapons, even for a new nuclear proliferant (see box 4-E). Both "hydrodynamic" tests of implosion characteristics (using a nonfissile core) and "hydronuclear" tests with extremely low nuclear yield can be used to lessen the need for full-scale nuclear tests in determining the adequacy of an implosion design.[74] Gun-type devices have even less demanding test requirements. If a proliferant state with competent designers decided in advance that no nuclear tests were to be carried out, it could pursue designs for fission weapons in the absence of those tests that would have a high probability of producing significant yields. Testing would be much more important, however, for a proliferant to develop either very low-weight nuclear weapons or thermonuclear weapons.

Weapon fabrication would also probably not present major technical hurdles to a proliferant. Assembly of a gun-type weapon is relatively straightforward. Implosion-designs would require lathes, other machine tools, and possibly isostatic presses to fabricate explosive lenses and other components, but there may be several suppliers of these dual-use items and various ways to import them. Little of the equipment for final assembly of a weapon is sufficiently specialized to be easily controllable by export laws. Some of the machine tools might be amenable to export monitoring, however, and may therefore serve as preliminary indicators of a program (see 'signatures' section below).

---

72 *Al-Atheer Plant Progress Report for the Period 1 January 1990 to 31 May 1990,* Annex to the Sixth Inspection Report, U.N. Security Council S/23122, Oct. 8,1991 (English), p. 14, reprinted as app. B of Peter Zimmerman, "Iraq's Nuclear Achievements: Components, Sources, and Stature,' Congressional Research Service report 93-323F, Feb. 18, 1993. See also p. 20 of main text.

73 Worlton, "some M@ about High-Performance Computers. . .," op. cit., footnote 69.

74 See, for example, Robert N. Thorn and Donald R. Westervelt, ''Hydronuclear Experiments,'' Los Alamos National Laboratory Report LA-10902-MS, February, 1987.

Box 4-E – Utility of Tests at Various Yields

The decision to test a nuclear weapon must weigh the benefits of validating the design against the risks and political implications of the test's being detected. Tests with substantial nuclear yields can provide important information about a weapon design, but they are likely to be detected. Certain aspects of nuclear bomb design can be validated even at very low explosive yields. The following TNT-equivalent-ranges illustrate possible uses for such tests:[1]

No nuclear yield: With proper diagnostics, scientists can study implosion techniques, compression efficiency, and neutron initiator performance by substituting nonfissile material for HEU or plutonium.

Less than 1 ***kilogram (kg)*** nuclear yield; So-called "hydronuclear tests" at these yieids were carried out by Los Alamos during the testing moratorium of 1958-1961 to study certain characteristics of nuclear warhead designs.

1 *to a few kilotons* (/d): Fission weapons of both gun-type and implosion designs can be tested at full or almost full yields in this range. in addition, tests involving boosted-fission designs may be carried out within this yield range (see **app. 4-A).**

150 kt: The Threshold Test Ban Treaty of 1974 between the U. S., U. K., and former Soviet Union forbids testing at greater than 150 kt yields. However, advanced nuclear powers can probably design thermonuclear warheads with up to multimegaton yields without testing above the 150- kt threshold.

Atmospheric tests: Above-ground tests can be used to measure electromagnetic pulse, radiation, blast, fallout, and cratering phenomena that are much harder, or impossible, to study with underground tests.

if a proliferant state decides not to carry out nuclear tests with appreciable nuclear yields, it could probably still design reliabie first- generation gun-type or implosion fission weapons with yields similar to the Hiroshima or Nagasaki bombs, With a small number of tests at yields of a few to 10 kt, it may also make progress toward developing more compact or efficient weapons, possibly incorporating boosting. Atmospheric tests are highly visible, but they are not required to verify the basic function of nuclear explosives.

[1] See, **for example, Ray E. Kidder, "Militarily Significant Nuclear Explosive Yields,"** *Federation of American Scientists Public Merest Report, vol. 37, No. 7,* **September 1985; and Dan Fenstermacher, "The Effects of Nuclear Test-ban Regimes on Third-generation-weapon Innovation,"** *Science & Global Security,* **vol. 1, Nos. 3-4 (1990), p. 193.**

EXPERIENCE FROM CIVILIAN NUCLEAR PROGRAMS

The infrastructure and experience gained from civilian nuclear research and nuclear power programs would be of substantial benefit to a nuclear weapon program. Up to a certain point in developing a civilian nuclear fuel cycle, its technology is virtually identical to that used for producing fissile materials for weapons. Relevant experience would include the ability to handle radioactive materials, familiarity with chemical processes for fuel fabrication and with materials having specific chemical or nuclear properties, and the design and operation of reactors and electronic control systems. Although this kind of experience is not unique to the operation of reactors--and is neither necessary nor sufficient to produce a weapon—it would provide a technology base upon which a nuclear weapon program could draw. Furthermore, the infrastructure supporting nuclear power generation and its associated fuel cycle can provide cover for elements of a weapon program, even in a country subject to IAEA safeguards.

RECRUITMENT, FOREIGN TRAINING, AND INDIGENOUS EDUCATION

The principles of nuclear weapons can be discovered without any prior design experience by any competent group of theoretical and experi-

mental physicists and engineers. Although the specifics of designing, analyzing, testing, and producing a nuclear explosive device are certainly not taught in graduate schools, nuclear engineering and physics curricula inevitably provide a basic foundation for work in the area of nuclear weapon design. Indeed, students from many countries each year go abroad for instruction in such fields at top universities.

A country wishing to pursue nuclear weapons can also adopt its design methodology to the expertise at hand. Given scientists with only limited confidence in their design ability, such a state might choose to develop a very conservative implosion design that was not highly dependent on the quality of compression, or a gun-type weapon using HEU that, while bulkier and requiring more fissile material, would be much easier to build. First-hand design experience would be essential only to develop more sophisticated concepts, such as advanced or boosted fission weapons, high yield-to-weight weapons, or second-generation (thermonuclear) weapons.

Nevertheless, the assistance of outside experts with specific knowledge of nuclear design can significantly accelerate a program by avoiding '(dead-ends?' that could waste valuable time and resources. Countries such as Iran, North Korea, Algeria, and Libya may well require a very long time if they were to start up a Manhattan-Project-like program, without access to experienced weapon designers. If too much time or money is required, then the risks of being discovered by outsiders (or even by internal political opposition) would increase, and a country may simply decide to abandon its program or not pursue it in the first place.

At least one case is already known, however, of one country's nuclear design information being used by another country's nuclear program. Yuli Khariton, the physicist who led the effort to develop the first Soviet nuclear weapon, recently admitted that the Soviets had obtained the design of the frost U.S. plutonium weapon shortly after it was used on Nagasaki. He claimed that this enabled the Soviets to carry out their first nuclear test 2 years ahead of schedule-in 1949 instead of 1951. He said that it was not until 1951 that they detonated a device based on their own design.[75] There have also been various unconfined reports of Chinese nuclear design information being used by Pakistan.[76]

According to the U.S. State Department, dozens of key Russian scientists would likely be able to direct critical aspects of a weapon program in a developing country, and perhaps 1 or 2 thousand technicians possess highly useful technical skills.[77] Several dozen nuclear scientists from the former Soviet Union (though probably not weapon designers) have reported been working in Iran, with dozens more entering other Middle Eastern countries.[78] Russian and Western specialists, however, say that so far they have no hard evidence that any attempt at recruiting actual nuclear weapon designers has been successful.[79]

In any case, the expertise needed to produce weapon-usable material *and* to make it into a deliverable weapon spans a wide range of disciplines and requires the right mix of individuals. Recruiting any given nuclear weapon specialist

---

75 Serge Schmemann, "1st Soviet A-Bomb Built from U.S. Data, Russian Says, " New *York Times,* Jan. 14, 1993, p. A12. Khariton claimed that the design was obtained with the help of spy Klaus Fuchs soon after the U.S. bombs were dropped on Hiroshima and Nagasaki in August 1945.

76 See, for example, Hedrick Smith, "A Bomb Ticks in Pakistan," New *York Times Magazine,* Mar. 6, 1988, p. 38.

77 "Redirecting the Soviet Weapons Establishment: An Interview with Ambassador Robert L. Gallucci," *Arms Control Today,* VO1. 22, No. 3, June, 1992, pp. 3-6.

78 Interview with David h-vi, director general of Israel's Defense Ministry, in Ethan Bronner, "Israel Fears a Flow of Lethal Expertise to the Middle East," *Boston Globe,* June 22, 1992, p. Al.

79 Paul Quinn-Judge, "In Republics, An Eye on Bombs, Scientists," *Boston Globe,* June *23, 1992,* p. A14.

could have significant or only marginal utility, and would depend strongly on the particular needs of a country at the time.

I costs

REQUIRED INFRASTRUCTURE

To develop nuclear weapons indigenously, a government must make a serious and long-term political commitment, must allocate significant amounts of resources and expertise, and must construct large facilities. (The required steps are summarized for uranium- and plutonium-based weapons in figure 4-1 and table 4-l). Since nuclear programs can vary tremendously, depending on a country's choices about paths, organization, secrecy, and goals, absolute costs are difficult to estimate. For instance, the path chosen by a country would strongly depend on its technical and industrial infrastructure, Moreover, the costs of developing the special nuclear materials cannot be directly compared with the costs of commercial enrichment facilities or spent-fuel reprocessing plants for nuclear power reactors, since facilities to produce only enough material for one or a few weapons per year can be tens of times more expensive per unit material processed than commercial facilities, but hundreds of times smaller. Steps to keep a program *clandestine can also* add considerably to the overall cost.

The Iraqi program, which appears to have been aimed at a small *arsenal* rather than a single weapon, took multiple paths and pursued its goals under tight secrecy. Starting in 1981, after the Israeli bombing of the Osirak reactor, Iraq apparently devoted its effort to producing enriched uranium instead of plutonium and began building complex research and production facilities (including twin sites for EMIS separation). Such a program can easily absorb much more money—*perhaps as much as* 10 *to* **50** *times more—than the* baseline plutonium-based program described below, and can run upwards of $10 billion.[80] Even then, it cannot be *assured* of success or of remaining secret. If nothing else, Iraq's program showed that there is a vast difference in cost between the cheapest direct route to nuclear weapons and a clandestine route taken by a country with little nuclear-weapon relevant experience, but relatively lofty nuclear ambitions.[81]

WEAPON MATERIALS DOMINATE THE COST

In general, the acquisition of sufficient quantities of weapon-grade materials presents not only the greatest technological hurdle, but also the greatest financial burden to the would-be proliferant. In the unlikely case that the government of a country without prior enrichment or reprocessing capability were to initiate a nuclear weapon program overtly, it could probably build a small production reactor and reprocessing plant more cheaply than it could produce equipment to enrich uranium. To remain hidden, however, a plutonium-based weapon program may have to take difficult and expensive measures. For instance, a proliferant might be driven to build a production reactor underground and to try to disguise its heat emissions to avoid being detected by infrared surveillance. If a country had no reason to reprocess spent fuel for commercial purposes, the discovery of a reprocessing facility would probably indicate weapons intent, so that steps might be called for to hide such a facility as well, or at least to keep it from being inspected.[82]

---

80 For comparison, the Manhattan District project spent $1.9 billion in 1940s dollars (which translates to about $10 billion in 1992 dollars): 50% to Oak Ridge for uranium enrichment 20% to Hanford for plutonium production and about 4% to weapon-related R&D at Los Alamos. See, for example, Zimmerman, op. cit., footnote **72, p. 4.**

81 See also Thomas W. Graham, ''The Economics of Producing Nuclear Weapons in Nth counties, '' *Strategies for Managing Nuclear Proliferation: Economic and Political Issues* (Lexington, *MA:* Lexington Books, 1983), pp. 9-27.

82 For instance, North Korea's claim that the facility at Yongbyon is for peaceful radiochemistry research (including separation Of plutonium) is particularly questionable, since that country's nuclear power industry is still in its infancy and could not be expected to derive benefits from plutonium recycling anytime soon.

Table 4-8-Nominal Costs for an Overt Small-Scale Plutonium-Based Weapon Program (in millions of 1992$)

Capital Costs of Construction:	
Uranium Mining Site (55,000 t ore/yr):	1.5-15
Milling Plant (100 t U_3O_8/yr):	8 - 9
Conversion Plant (85 t uranium-metal/yr):	12-14
Fuel Fabrication Plant (85 t natural-uranium-fuel/yr):	6-10
30-MWt Production Reactor: (Brookhaven-type, air-cooled, graphite moderated, aluminum-dad natural uranium fuel; lower cost is for "stripped down" facility with little shielding)	35-100
PUREX Reprocessing Plant:[a] (85 t heavy metal/yr, very low burn-up fuel, batch processing, recovering about 10 kg plutonium/yr; low estimate is for rudimentary facility with little radiation shielding)	12-36
RDT&E costs for the above facilities:[b] (10% - 15% of the capital costs)	10-30
Start-up costs for the above facilities: (20°/0 - 25% of the capital costs)	15-45
Design and manufacture of the first nuclear weapons: (includes capital costs of the weapon laboratory, RDT&E of the design phase, and nonnuclear components; 20-25% of the total cost of plutonium production (all above costs))	20-65
Total cost of first plutonium-based weapon:	$120-$300 million

a PUREX stands for plutonium-uranium redox extraction process, a widely used method whereby uranium and plutonium are removed from spent fuel through a series of chemical processes.
b Research, development, testing, and engineering. This and the "design and manufacture" costs are based on early British and French nuclear weapon experience. Figures are adjusted to account for assumed cost reductions in RDT&E that resulted from "international nuclear learning" that took place most rapidly between about 1955 and 1960.

SOURCE: Adapted from Stephen M. Meyer, *The Dynamics of Nuclear Proliferation* (Chicago, IL: Univ. of Chicago Press, 1964), pp. 194-203.

A minimum-cost plutonium program

One detailed study has estimated that facilities sufficient to produce about one nuclear-weapon's worth of plutonium per year could be built for as little as $120 to $300 million (in 1992$), if the state building it did not try to keep it secret (see table 4-8).[83] This estimate includes the necessary uranium mining and processing facilities, a small production reactor to produce the plutonium, and a primitive reprocessing plant to recover it. Since few if any countries are likely to initiate such a program openly, this number is unrealistically low, but it can serve as a point of comparison for more detailed country-specific assessments.

According to this study, a country that has deposits of uranium ore could setup mining and ore processing (called "milling") facilities that would be sufficient to fuel a small production reactor in roughly 2 years, and without major expense or difficulty. Fuel fabrication, in theory, could be done in a common metalworking shop, although typically it has required imported facilities. The production reactor itself could be based on the Brookhaven Graphite Research Reactor, a 1955 design that has long been described in

83 Stephen M. Meyer, *The Dynamics of Nuclear Proliferation* (Chicago, IL: Univ. of Chicago Press, 1984), pp. 194-203. Also see the earlier cost-estimate studies done by the United Nations in 1%8 and by the U.S. Energy Research and Development Administration (ERDA) in 1976, as discussed in Graham, ''The Economics of Producing Nuclear Weapons in Nth Countries, ' op. cit., footnote 81.

unclassified U.S. Atomic Energy Commission documents. It is rated at 30 MW thermal output and if devoted to plutonium production, could produce enough for at least one nuclear weapon a year. (If a state seeking to build such a reactor could not do so indigenously, it could be forced to import specialized reactor components such as ultra-pure graphite. Such imports from an NPT state would trigger safeguards.)

Data regarding the design, construction, and operation of reprocessing facilities were also declassified and distributed through the 1955 Geneva conference on the peaceful uses of atomic energy. However, despite using chemical processes similar to those in standard industrial procedures, the reprocessing plant could be the most difficult step in this approach, due to the radiological hazard it would pose to plant workers. Nevertheless, radiation risks can be minimized (and the quality of the plutonium for weapon use improved) by irradiating the fuel to levels that are extremely low compared to those attained by commercial reactors—say, a few hundred megawatt-days per tonne of fuel (MWd/t), as opposed to 10,000 to 33,000. A small reprocessing facility could probably be built over the course of 3 to 4 years.

The total number of competent, experienced engineers needed over the course of several years to direct the construction of a Brookhaven-type graphite-moderated reactor and an associated reprocessing plant has been estimated to be about 10 to 20, together with a workforce of several hundred.[84] Cost estimates for the entire program (adjusted to 1992 dollars), including mining, milling, and fuel-fabrication facilities, are itemized in table 4-8. Many developing countries with a modest technical infrastructure could construct such facilities, and the cost of obtaining the trained specialists would constitute only a small fraction of the total weapon-program costs.

Reports in the open literature indicate that two countries have pursued unsafeguarded production reactors of approximately the size assumed here, although their cost data are not known. North Korea recently declared that one of its two operating reactors at Yongbyon is rated at 5 MW(e), but many Western analysts believe it is a 30 to 50 MW(t) production reactor.[85] Unofficial reports have alleged that Pakistan may have begun building a similarly rated (50 MW(t)) reactor in the mid-to-late 1980s.[86]

A more ambitious program aimed at indigenous construction of a 400-MW(t) production reactor and 10 to 20 weapons per year would require either a fairly high level of industrialization or a considerable nuclear technology base upon which to build. The only known *unsafeguarded* reactors with roughly this output (outside the five declared nuclear weapon states) are the five 220-MW(e) heavy -water reactors (HWRs) operating in India, and possibly Israel's Dimona HWR, believed by most to have operated at 40 to 70 MW(t),[87] but by some at up to 150 MW(t).[88] India has five other indigenous HWRs under construction, and North Korea has recently declared that is it constructing two power reactors with approximately this power rating-a graphite power reactor at Yongbyon rated at 50 MW(e) (in addition to two smaller reactors already in operation there), which would give it a thermal output of 150 to 200 MW(t), and a larger reactor at Taechon projected to have a power rating of 200

---

84 Meyer, ibid.

85 See testimony of R. James Woolsey, Feb. 24, 1993, op. cit., footnote 15; and Spector, *Nuclear Ambitions,* op.cit., footnote16, pp.128, 139.

86 See Spector, Nuclear *Ambitions*, op. cit., footnote 16, p. 116.

87 Ibid., pp. 83-4, 172.

88 "Revealed: The Secrets of Israel's Nuclear Arsenal, *Sunday Times* (London), Oct. 5, 1986, p. Al.

MW(e) (roughly 600 MW(t)) once completed.[89] By one estimate, a reactor of several hundred MW(t) would normally take 5 to 7 years to complete, would require an overall capital investment in the range $400 to $1,000 million (1992$), and would require about 50 to 75 engineers supported by roughly 150 to 200 technicians for its design and construction.[90] Others estimate that practical difficulties normally encountered in constructing such facilities could increase these figures by up to 100 percent.[91]

Costs for small-scale uranium enrichment

Costs for a dedicated (and possibly clandestine) enrichment facility are extremely difficult to estimate, both because the procurement route and choice of technology are much more uncertain than for an indigenously built reactor and reprocessing plant, and because experience and openly published data relevant to enrichment facilities tend to be associated with very large commercial plants built for the nuclear power industry. (The cost can be much cheaper per unit enrichment capacity for large plants,) Nevertheless, a nominal idea of costs can be derived from smaller commercial facilities. Excluding research and development, the total cost for constructing a centrifuge facility capable of producing 300 kg HEU per year-12 times the IAEA significant quantity-might run from $100 to $500 million (in 1992$).[92] A smaller facility to produce about 15 kg of HEU per year based on calutron (EMIS) technology has been estimated to cost a minimum of $200 million.[93] If a sma11 amount of additional enrichment capacity-say, enough for 30, rather than 300, kg of HEU per year-were to be built by a country already knowledgeable about the manufacture and operation of centrifuges, the costs could conceivably be much lower, perhaps only $2 to $5 million. The costs of building and operating such a facility in secret at a clandestine location, however, might increase this figure substantially.

| Implications of New Materials-Production Technologies

URANIUM ENRICHMENT TECHNOLOGIES

Although France, Japan, and the United States have made substantial progress in the last 10 years developing laser enrichment processes, successfully integrating laser or other advanced technologies into a facility capable of producing kilogram-quantities of HEU will probably remain beyond the reach of the developing countries for some time. Even in the most technologically advanced countries, these methods have tended to require a lengthy development period, and the quantities of material produced in the early stages has been very small. In contrast, technologies such as aerodynamic methods and centrifuges may offer potential proliferants a more attractive mix of characteristics. As evidenced by South Africa and Pakistan, these techniques appear capable of being developed successfully by countries having either a substantial technology base or access to sensitive design data.

---

89 Choe Jong Sun, spokesman for North Korean Ministry of Atomic Energy Industry, in interview with Leonard S. Spector, May 3, 1992, Pyongyang, as posted on Nuclear Nonproliferation Network.

90 Meyer, The *Dynamics of Nuclear proliferation, Op. cit.,* footnote 83.

91 George Anzelon, associate division leader of Z-Division, Lawrence Livermore National Laboratory, private communication Aug. 16, 1993.

92 U.S. Congress, Office of Technology Assessment, *Nuclear Proliferation and Safeguards,* op. cit., footnote 24, P. 180.

93 Oswald F. Schuette, ''Electromagnetic Separation of Isotopes, '' in OTA, *Nuclear Proliferation and Safeguards,* op. cit., footnote 24, vol. II, Part 2-VI, p. 105; costs have been converted to 1992 dollars.

TECHNOLOGIES AFFECTING PLUTONIUM FUEL CYCLES

Plutonium isotopic purification

The longer that reactor fuel containing uranium-238 is irradiated in a reactor, the higher will be its proportion of undesirable isotopes in the plutonium that is created, making it less desirable for nuclear weapons than pure plutonium-239. (See app. 4-A and the discussion earlier in this chapter on the use of reactor-grade plutonium in nuclear weapon s.) Just as uranium-235 can be separated from uranium-238 to obtain bomb-grade material, so can plutonium-239 be separated from these other plutonium isotopes. Laser isotope separation (LIS) techniques, for instance, although not originally developed for that purpose, might be used.[94] Plutonium-239, in theory, could also be ''enriched' using centrifuges, EMIS, or even gaseous diffusion methods, though developing conversion facilities to produce the requisite plutonium compounds would be a major undertaking rife with its own set of problems.

Liquid-metal fast breeder reactors (LMFBRs)

Development of LMFBRs (reactors that are capable of breeding plutonium at a faster rate than they consume it) has progressed much less rapidly than was predicted in the 1970s. The principal breeder reactor programs have been located in Japan, France, and the former Soviet Union (mainly in Kazakhstan) .95 But France suspended operation of its 1,200-MW(e) production-scale FBR, called Superphenix, in 1990, and Germany and the U.K appear to be abandoning their efforts to develop breeders.

LMFBRs introduce safeguard concerns far beyond those faced with the light-water reactors (LWRs) most commonly used for power generation. Whereas reprocessing can be forgone for LWRs, it is integral to a breeder's fuel cycle. Fresh LMFBR fuel contains a considerably larger fraction of plutonium than does even the plutonium-containing MOX fuel intended for use in commercial LWRs. (LMFBRs such as Superphenix contain about 5 tonnes of plutonium in their cores.) Moreover, a considerable amount of the plutonium produced in an LMFBR under normal operation will be weapon-grade, whereas commercial light-water reactors produce much lower quality (reactor-grade) plutonium unless shut down and refueled much more frequently than economical operation would warrant.

Integral Fast Reactor **(IFR)** fuel cycle

In the future, new plutonium fuel cycles could also be developed and commercialized. One such concept, which has been under development by Argonne National Laboratory in the United States for many years, is called the Integral Fast Reactor (IFR),[96] The IFR was originally developed to reduce the amount of nuclear waste generated by reactors by "burning" more of the longest lived radioactive byproducts than can be consumed by conventional nuclear reactors. The reprocessing approach used in an IFR fuel cycle would produce plutonium-containing fuel that is considerably more radioactive than that resulting from the traditional PUREX process, thus being less attractive for diversion to a weapon program. To handle it efficiently, reprocessing would occur at

---

94 In the 1980s, the U.S. Department of Energy's plans for a laser isotope separation facility to be built in Idaho included separating plutonium isotopes. Although economically unattractive compared with more direct methods of obtaining nuclear weapon materials, the possibility of using LIS to enrich plutonium has added somewhat to the concern over the Japanese and South African development of pilot I-IS plants. Although both countries already operate reprocessing facilities and have legitimate needs for enriched uranium for nuclear power, the purification of separated plutonium would provide an additional path for producing weapon-grade plutonium.

95 Kazakhstan's 335-MW(t) fast breeder (BN-350) dates from Soviet efforts over the past 10 to 20 years and is designed to use 20 to 25% enriched uranium as well as MOX fuel. Potter et al., op. cit., footnote 35, p. 9.

96 Charles E, Till and Yoon I. Chang, ''The Integral Fast Reactor,' *Advances in Nuclear Science and Technology,* vol. 20 (1988), pp. 127-154.

the reactor site itself, in hot cells as close as 100 feet to the reactor.[97]

The proliferation concerns with the IFR fuel cycle, as with other fuel cycles involving reprocessing, center on the accountability requirements to assure nondiversion of nuclear material at any stage. Since the hot-cell area is small and has relatively few access points compared to the PUREX process, it would be more difficult for subnational groups to divert material from an IFR. However, because the IFR concept would require a closed-cycle inert-gas environment involving highly radioactive materials at high temperatures, effective materials-accountancy may be difficult to implement. Instead, safeguards will have to rely much more heavily on containment and surveillance measures (see app. 4-Con IAEA safeguards and the civilian nuclear fuel cycle). Although the prospect of IFRs substituting for conventional LWRs in the United States or even for liquid-metal breeder reactors in France or Japan does not appear to be likely for several decades, the long-term proliferation and safeguards implications of sharing IFR reactor technology with other countries is yet to be fully addressed .98

| Weaponization-Going Beyond the "Physics Package"

MINIATURIZATION

A nuclear device deliverable by aircraft or missiles at long range must meet certain size and weight constraints. The bombs used in World War II, called "Little Boy" and "Fat Man," each weighed in excess of 4,000 kg, which would have made them virtually impossible to deliver by any ballistic missile deployed in the Third World today, and problematic for over half these countries' combat aircraft, including the F-16, Mirage F-1, MiG-23, -27, and -29. (Chapter 5 discusses delivery systems suitable for nuclear weapons as well as chemical or biological weapons, and provides more detail on the capabilities of aircraft and missiles available to states of proliferation concern.)

A nuclear proliferant today could probably construct a much lighter bomb than the first U.S. bombs. Many experts believe that even the 500-kg payload limit originally set by the Missile Technology Control Regime (and since eliminated at the beginning of 1993) may no longer be appropriate for first-generation nuclear weapons. U.S. 8-inch and 155-mm nuclear artillery shells produced in the late 50s and early 60s suggest that compact and relatively lightweight warheads can indeed be designed. Although the design of these warheads drew on the experience gained from hundreds of nuclear tests, they may still have relevance to current proliferation concerns for several reasons. First, explosives technology and light-weight electronics have advanced dramatically since the 1950s. Second, other forms of testing, such as "hydronuclear tests" with extremely low nuclear yields (see discussion below) may allow at least the more technologically advanced proliferant countries to reduce amounts of materials in their weapon designs to levels well below those of the first U.S. weapons. Third, at least some knowledge of more advanced weapon designs (even if from three decades ago) maybe difficult to keep out of the hands of proliferants. Finally, even straightforward modifications to the designs of the first U.S. weapons could reduce their size considerably, albeit with some yield penalty, with no greater required sophistication. The mere fact that the United States has built low-weight nuclear weapons indicates that they *can* be built, considerably increasing a proliferant's motivation to attempt to recreate such a

97 The IFR can use more radioactive nuclear fuel because it is less sensitive than many other types of nuclear reactor to fuel impurities that absorb neutrons.

98 See, for example, R.G. Wymer et al., "An Assessment of the Proliferation Potential and International Implications of the Integral Fast Reactor," prepared by Martin Marietta Energy Systems, Inc. for the U.S. Dept. of Energy and the U.S. Dept. of State, May 1992.

design. Their existence also offers the possibility that such designs might be stolen, particularly if the Soviet Union and other nuclear weapon states have developed low-weight warheads as well.

ANTI-AGING

Unless assembled immediately prior to use, warheads would have to be storable over some period of time to be militarily useful. To make warheads that were reliable after years of storage, many features might need refinement, including nondegrading high explosives, purer grades of plutonium[99] or, with weapon designs that use tritium gas for additional yield, a replaceable tritium supply. Anticorrosive materials might be required at various points within the weapon, in addition to metallurgically stabilized nuclear material. Some of these refinements might require substantially more research than what would be needed for a crude frost-generation weapon. Frequently recycling the nuclear material, reassembling the weapon, and inspecting the nonnuclear components could ameliorate these problems, but such measures introduce considerable logistical problems of their own.

REENTRY VEHICLES AND FUZING

As mentioned above, missile delivery would place constraints on a warhead's size and weight. For Scud-type missiles, which do not employ a separating reentry vehicle, these constraints are not severe. However, if a narrow cone-shaped reentry vehicle were deemed necessary to achieve desirable aerodynamic properties, it would have to be internally balanced to avoid wobbling or tumbling.[100] Such reentry vehicles would constrain the configuration of a warhead's high explosives and detonators, possibly requiring a more sophisticated design that a proliferant might wish to test in order to have high confidence in its performance.[101] It might also be desirable to incorporate radar altitude-fuzing, to avoid the added difficulty of designing weapons to detonate on impact, or *salvage fuzing* (detonation upon being attacked by an interceptor) to defeat missile defenses. These features would likely require flight testing of the reentry vehicle under realistic conditions before fielding it and would thus increase a program's visibility as well as its technical hurdles.

SIGNATURES OF NUCLEAR PROLIFERATION ACTIVITIES

The IAEA safeguards system provides a means of monitoring and inspecting peaceful nuclear activities in a great number of countries. In addition, however, individual countries may wish to monitor the potential for other countries to develop nuclear weapons—both to evaluate and deal with the security threat that such programs could pose and to assess the effectiveness of and possible improvements to nonproliferation policies. Every stage of nuclear weapon development, from material production to deployment, can generate signatures that provide some indication of a weapon program's existence or status, although only a few of them point fairly unambiguously to a nuclear weapon program.

This section surveys potential signatures of a nuclear weapon program without attempting to fully assess the capability to monitor nuclear proliferation or verify compliance with the NPT; such would require evaluating the capability to observe these signatures, identify them, and piece

---

99 Plutonium-241, an unwanted plutonium isotope, decays into americium-241, which is much more radioactive than plutonium. As it builds up within a weapon, that weapon becomes more difficult to work with and its characteristics can change. Higher grades of plutonium have less plutonium-241, thus reducing these problems.

100 Although the principal reason that the acknowledged nuclear powers have attempted to prevent their missile warheads from tumbling or wobbling during reentry is to attain higher *accuracy,* a tumbling warhead's violent motions and potential lack of adequate heat shielding could also affect *reliability.*

101 Testing would also be much more important if a proliferant were seeking to develop very low-weight warheads to accommodate limited payload capacities of certain types of ballistic or cruise missile.

them together with other sources of information to arrive at timely conclusions regarding particular states' activities.

Materials Acquisition

URANIUM OR PLUTONIUM DIVERSION FROM SAFEGUARDED FACILITIES

Under the mandate of the NPT, IAEA safeguards focus narrowly on a specific goal-timely detection of diversion of *significant? quantities* of fissile nuclear materials from facilities declared to be peaceful in purpose (see app. 4-C on safeguards). The detection of such diversion, or the discovery of unsafeguarded nuclear facilities in a state that had committed to place all its facilities under safeguards, would generate strong suspicions of a nuclear weapon program.

Safeguards primarily operate indirectly, by verifying that all nuclear materials are accounted for. (They are supplemented at certain types of facility by *containment and surveillance* techniques, which in principle could detect some types of diversion directly.[102]) *Material accountancy* seeks to verify the correctness of a plant's own operating records, much as an audit of a financial institution verifies its bookkeeping. Over the past 15 years, material accountancy techniques have improved significantly. Safeguards also make extensive use of automated equipment for measuring controlled items and for supporting containment and surveillance techniques.

In addition to evidence of diversion acquired through material accountancy or containment and surveillance, certain *behaviors* might also raise doubts about a safeguarded country's intent to comply with its nonproliferation agreements. Behaviors detectable through normal safeguards inspections could include: stalling tactics (e.g., unsubstantiated complaints about individual inspectors or repeated exclusion of inspectors with certain nationalities)[103]; barring inspectors' access to certain areas or facilities for suspicious reasons; having substantial or repeated *material-unaccounted-for* (MUF)[104]; or keeping inconsistent records. If detected by other means, construction of undeclared 'pilot facilities that appeared to be destined to contain nuclear material would also raise suspicions, as would refusal of an IAEA request for a special inspection at such a facility.[105]

URANIUM ENRICHMENT

If operated on a large enough scale (perhaps 10 bombs-worth per year), an energy-inefficient enrichment technology such as EMIS or gaseous diffusion might be detectable by its heat emission. At Iraq's A1-Tarmiya facility, for instance, heat rejection into the air or, as appears to have been planned, into the Tigris river, might well have been observable once operation had begun.[106] However, at lesser production rates or with more

---

102 Containment and surveillance equipment includes unattended video cameras, motion detectors, closed-circuit TV systems, and various types of seals.

103 Under IAEA safeguards, a country has the right to reject inspectors of whatever nationalities it chooses (Or, for that matter, fOr any other reason), a right that is regularly exercised. For example, between 1976 and 1981 (the year that Israel attacked the Iraq's Osirak reactor), Iraq allowed only Soviet and Hungarian nationals to perform safeguards inspections on its territory. Testimony of Roger Richter, former IAEA inspector in Iraq, cited in J. Aroesty, K.A. Wolf, E.C. River, *Domestic Implementation of a* Chemical *Weapons Treaty,* Rand Report R-3745-ACQ (Santa Monica, CA: RAND Corp., Oct. 1989), p. 55,

104 "Material-unaccounted-for" is a safeguards term describing differences between measured and expected values in material accountancy. MUF can result from normal measurement or calibration errors, or can indicate a possible diversion of materials.

105 See, for example, George Bunn, *Does the NPT Require its Non-Nuclear Weapon Parties to Permit Inspection by the IAEA of Nuclear Activities That Have Not Been Reported to the IAEA?* (Stanford, CA: Center for International Security and Arms Control, Stanford University, April 1992).

106 Anthony Fainberg, *Strengthening IAEA Safeguards: Lessons from Iraq* (Stanford, CA: Center for International Security Arms Control, Stanford University, April 1993), p. 21.

efficient technologies (e.g., centrifuges, or EMIS techniques that employed permanent magnets and lower beam-voltages), heat signatures would be less evident. Heat emission is a nonspecific signature, however, that would be most useful for monitoring the startup and shutdown patterns of known facilities; it would have to be combined with other indicators to determine whether a given unknown facility were nuclear-related.

A potential sign of a clandestine enrichment or other nuclear facility could be unexplained special security or military reinforcements around an industrial site. These arrangements might be visible from overhead or from the ground.

At close enough range, other signatures would become observable. For example, even a very small centrifuge plant might emit detectable acoustic or radiofrequency noise, and the pulsed lasers used for laser isotope separation emit characteristic electromagnetic signals at kilohertz frequencies that might be detected, Samples of substances taken from either declared or suspect facilities could also indicate their potential for producing weapon materials. For example, UCL_4 or other uranium chloride combinations could indicate EMIS or Chemex enrichment technology, and UF_6, UF_4, HF, or uranium metal could indicate other uranium enrichment techniques (see app. 4-B).[107] Analysis of environmental samples containing depleted or enriched uranium in water or soil would also provide very important signatures.

Patterns of foreign procurement of essential materials and parts, such as newer high-strength materials or maraging steel (a very high-tensile-strength steel used to manufacture some types of gas centrifuge), or large iron electromagnets, high-voltage power supplies, and large vacuum systems (for EMIS), might also help to indicate a county's intentions.

PLUTONIUM PRODUCTION

An indigenous uranium mining industry might provide early indication of a clandestine uranium or plutonium-based weapon program and is a sure indicator of at least the possibility. For the plutonium path, natural uranium could fuel a graphite- or heavy-water moderated plutonium-production reactor. A sizable research program involving breeder-reactors or the production of heavy water or ultra-pure carbon and graphite products might also be cause for concern, especially if such programs were not easily justifiable on other accounts.

Small research or power reactors with high neutron flux and significant amounts of uranium-238 in their cores can also be used to produce plutonium. However, a 40 to 50 MW(t) undeclared reactor (enough to produce plutonium for at least one bomb per year) should be easily discernible to overhead infrared sensors, at least if it is built above ground and located away from heavy industrial areas (such a location might be chosen for security and safety reasons anyway).[108] Insections of *safeguarded* **reactors,** especially if carried out at more random intervals, might detect unnecessary placement of uranium-238 in or around the core, augmenting the rate of plutonium production. Similarly, inspections of CANDU-style reactors (a heavy-water-moderated reactor that can be refueled online) or of frequently shut-down LWRs should call attention to very low-bum-up fuel cycles, from which the plutonium produced is predominantly plutonium-239, the isotope best suited for weapons.

---

107 Note, however, that the specific compounds UCl_4 and UF_6 would not likely be found in the atmosphere, Skim they react very quickly with water to form other compounds. The existence of UF_4 might also be evidenced by the particular processing equipment required to reduce it to metallic form.

108 If the heat were discharged into a modest-sized river, a resulting rise in temperature on the order of O. 1 °C or more (depending on flow-rate, mixing, etc.) would be detectable in the far-infrared. Alternatively, heat from the cooling towers might also be detectable. See Fainberg, *Strengthening IAEA Safeguards,* op. **cit., footnote 106, p. 21..**

SPENT-FUEL REPROCESSING

In general, the plutonium-production route, which involves reprocessing of spent reactor-fuel to extract plutonium, would be easier to detect than would be a small-scale clandestine uranium-enrichment facility.[109] Plutonium and uranium from spent fuel (as well as enriched uranium from research reactor cores), is reclaimed by chopping up and dissolving the fuel elements in acid, subjecting the solution to solvent-extraction and ion-exchange processes, and chemically converting the plutonium and uranium in the resulting liquids to metallic or oxide forms. Methods for doing this, including the most common one, known as PUREX, involve various well-understood chemical processes that use characteristic groups of materials.

Detection of these materials, either by environmental sampling or by impactions, could indicate reprocessing activity.[110] Some chemicals might also be observed through export monitoring; for example, high-purity calcium and magnesium, which are used in the metal-conversion step, are included in the Nuclear Supplier Group's new list of sensitive dual-use items to be subjected to export controls (see app. 4-D).

Release of noble gases

In addition to the characteristic chemicals used in the PUREX process, effluents from reprocessing plants will contain telltale radioactive fission products, including radioactive isotopes of the noble gases xenon and krypton-especially krypton-85—and possibly argon.[111] Measurements made at the U.S. reprocessing facility at the Savannah River Plant in South Carolina have suggested that krypton-85 may be detectable, even from small facilities, at ranges of 10 kilometers or more.[112]

Isotopic content of plutonium

Analysis of plutonium samples or effluents from reprocessing could provide further evidence of *weapon intent* by revealing the fuel's irradiation level. For most types of reactor, a very low fuel-irradiation level would be a strong indicator of weapon activity. In addition, isotopic correlation techniques-which compare the isotopic ratios of different samples of plutonium-can provide sensitive indicators of plutonium production history or material diverted from one facility to another.[113]

Weapon Design and Intent

ACTIVITIES OF SCIENTISTS

The effort required to develop nuclear weapons can have a significant effect on the movement, publications, and quests for information of a country's leading scientists. Although publications on nuclear materials and reactors would be expected in connection with legitimate safeguarded activities, a sudden decline in these publications might be suspicious. Scientists directed to pursue a weapon program might begin seeking out specialized computer codes (especially adapted to high pressure and high temperature regimes) or attending a greater number of technical conferences in the areas of optical instrumentation, reactor-core neutronics, or high-explosives and shock-wave hydrodynamics. They

---

109 *Any* unsafeguarded experimentation with reprocessing by an NPT nonnuclear-weapon state would be suspicious, and reprocessing activity has traditionally been a cause for concern in any nonnuclear-weapon states, whether party to the NPT or not.

110 Various acids, organic and inorganic solvents, and other chemicals are used in the PUREX process, as well as uranium and plutonium that would be present at each step. See, for example, Richard R. Paternoster, ''Nuclear Weapon Proliferation Indicators and Observable,' Los Alamos National Laboratory, LA-12430-MS/UC-700 (December 1992).

111 Frank von Hippel and Barbara Levi, '' Controlling Nuclear Weapons at the Source: Verification of a Cutoff in the Production of Plutonium and Highly Enriched Uranium for Nuclear Weapons, " Kosta Tsipis et *al.*, Arms Control Verification: *The Technologies That* Make it *Possible* (Washington DC: Pergarnon-Brassey 's, 1986), pp. 351-53.

112 Ibid.

113 Alex DeVolpi, Argonne National Laboratory, private communication, Dec. 14, 1992.

might also begin purchasing large numbers of declassified documents from foreign weapon laboratories. (Such documents were indeed found among those seized in Iraq.) A sudden recall of trained scientists from other countries would be another observable, as would attempts to recruit foreign weapon scientists.[114] Sending large numbers of graduate students abroad to study technical fields related to nuclear weapon design *might* be associated with a weapon program. However, such a signature would be very ambiguous, since at the graduate level, most such fields have widespread application.

DECLARATIONS OF LEADERS

Public statements by high officials can also shed light on a nation's intentions, though they must be interpreted *within* a given political context. For instance, statements from Iraq before the 1991 Persian Gulf War and from Iran after that war could be interpreted to indicate a desire for weapons of mass destruction:

> . . . it behooves us to declare clearly that if Israel attacks and strikes, we will strike powerfully. If it uses weapons of mass destruction against our nation, we will use against it the weapons of mass destruction in our possession.[115]
>
> Since Israel continues to posses nuclear weapons, we, the Muslims, must cooperate to produce an atom bomb, regardless of U.N. attempts to prevent proliferation. [116]

NUCLEAR AND HIGH-EXPLOSIVE TESTING[117]

Implosion physics

Repeated high explosive (HE) tests are generally required before a workable implosion-type nuclear weapon can be designed.[118] Explosive tests to study either the HE alone or its ability to propel metal objects would usually require electronic or optical instrumentation. For observers at close enough range, some indicators of high-explosive testing activity are the following:[119]

- expansion of facilities or personnel at or near an existing ordnance plant;
- purchase or production of explosives more energetic than pure TNT, such as RDX, HMX, or PETN, any of which could be mixed with TNT;
- equipment for compacting or melting and casting HE, perhaps modified from what would be used at a standard ammunition loading plant;
- alternatively, for different types of explosives, isostatic or hydrostatic presses, weighing many tons and likely remotely controlled (some antitank shaped-charges are also made using such presses);
- precision, possibly template or computer-numerically controlled, two-axis machining facilities for HE, especially if suited for machining curved contours and surrounded by blast-protection shielding;

---

114 Reports in the press have claimed that Iran recently appealed to emigre nuclear engineers to return home, ostensibly to work on civilian applications of nuclear power.

115 Speech by Saddam Hussein at the opening of the Arabs ummit conference in Baghdad, May 28, 1990, translated in FBIS-NEA, May 29, 1990, p. 5.

116 Iranian Vice President Ataollah Mohajerani, Oct. 25, 1991, at an Islamic conference in Tehran, quoted in George J. Church, "Who Else will Have the Bomb?" *Time*, Dec. *16,* 1991, p. **47.**

117 This and the following section draw heavily on material found in paternoster, "Nuclear Weapon Proliferation Indicators and Observable,' op. cit., footnote 110.

118 In order to improve the symmetry and effectiveness of the implosion, multiple experiments would be called for, including measurement of the resulting core density.

119 Paternoster, "Nuclear Weapon Proliferation Indicators and Observables,'' op. cit., footnote 110, pp. 7-9.

- waste and scrap from the above operations, possibly including effluent waste-water systems involving filters or catch basins; pronounced red coloration in waste water caused by dissolved TNT; solid scrap periodically destroyed by burning or detonation; and
- instrumented firing stations and control bunkers for HE or HE-metal tests using charges weighing up to hundreds of pounds.[120]

Test-firing of HE-metal systems containing uranium would be indicated by the following:

- bright streamers radiating from the test (caused by burning fragments of uranium) visible to the eye;
- local debris or dust that contained uranium; and
- nearby fire-extinguishi.ng equipment, portable radiation monitoring equipment, or permanent air-sampling radiation-monitors.

Since highly dense (but nonfissile) uranium-238 is widely used in certain types of antitank weapon, these indicators could also stem from advanced nonnuclear munition programs. Therefore, most or all of these could be associated with conventional munitions production and do not give unambiguous evidence of nuclear weapon development. However, *spherically symmetric* implosions would be more likely connected with a nuclear program.

Gun-type weapon development

Gun-type weapons generally require highly enriched uranium surrounded by neutron-reflecting material such as natural uranium, tungsten alloy, or beryllium metal or oxide (ceramic). A development program might use hundreds of pounds of beryllium or thousands of pounds of uranium or tungsten for the neutron reflector alone. Unusually high importation of some of these items by certain countries might suggest weapon-development activity. In addition,

- ground cover at the detonation test-site may be cleared in only one direction, since the debris from tests-and especially burning uranium streamers if natural uranium were used as a mockup for HEU-would be concentrated in a cone coaxial with the direction of projectile firing (however, a test program for *nonfissioning* shaped charges or kinetic-energy rounds could also have such a configuration);
- special fast-acting very-high-pressure gauges might be used to record the pressures in the gun breech; and
- distinct acoustic features might be observable.

NUCLEAR LABORATORY EXPERIMENTS

Observers who had access to suspicious laboratories might detect the following signatures:

- Criticality tests—weapon designers using near-critical fissile assemblies may wish to measure criticality with closed-circuit television and neutron counters in remotely operated (possibly underground) experiments. However, experiments can also be performed at the bench-top level, not needing elaborate equipment, and much of the relevant data is already available in the open literature. Moreover, similar facilities are also used for agricultural and biological neutron-irradiation research. Any kind of criticality accident at a suspect site, however, would be a strong indicator of weapon-design activity, since other applications would be ununlikely to work with near-critical assemblies.
- Neutron background measurements—for gun-type devices, neutron-flux measurements would be required to assure that background neutron counts were sufficiently low. Such measurements might be indicated by a room containing neutron detectors that was shielded from external sources of neutrons, for exam-

[120] Instrumentation could involve a few dozen high-speed oscilloscopes, high-speed rotating mirror 'streak' cameras; electronic-image-converter or high-speed framing cameras; and pulsed x-ray generators.

ple with water- or polyethylene-filled walls. Such facilities might also be used to test neutron initiators.

- Development of neutron initiators-neutron initiators produce a pulse of neutrons to initiate the nuclear chain reaction at the optimum moment (see app. 4-A). They use either alpha-particle-emitting radioactive substances or small particle accelerators containing radioactive tritium gas,[121] Therefore, import or production of alpha-emitting materials, tritium, or the special facilities to handle them (similar to those used for spent-fuel reprocessing) could indicate weapon development. However, small accelerator-based neutron sources are produced commercially for oil-well logging and laboratory use, so that they do not necessarily indicate a weapon program.
- Special tests—Since neutron initiation is so important to the proper detonation of a nuclear device, tests involving actual HE with very small (sub-critical) amounts of nuclear material would likely be carried out as well. These might be conducted in shallow underground chambers designed for neutron shielding. (A series of such tests, called ‘ ‘hydronuclear experiments,’ was conducted by the United States during the testing moratorium of 1958 -61.) Some of the surface equipment associated with these tests might also be telling.[122]

WEAPON FABRICATION

Final assembly of nuclear weapons can take place at small facilities. Indicators of such facilities could include special security arrangements and structures designed to handle accidental detonation of high explosives. These signs, however, could also indicate conventional military facilities.

Import patterns of dual-use items might again provide indicators of intent to fabricate weapons. During their inspections of weapon facilities in Iraq, the IAEA found items such as computer-numerically controlled (CNC) machinery, two-axis lathes, vacuum furnaces, and isostatic presses that had been imported through a vast network of foreign suppliers and front companies (see box 4-F). Since this equipment has a variety of industrial and nonnuclear military uses, it would be very difficult to determine its exact connection to a nuclear program simply by knowing the quantities being imported. Nevertheless, if sufficient monitoring could be implemented to detect and analyze *changes or unusual patterns* of import, or if reliable accounts of these items’ ultimate end-use could be kept, tracking some subset of dual-use equipment might provide an indication of weapon development. The import of a suite of multiuse items would provide more important information than that of individual items.

Effluents and solid waste from a suspected weapon-fabrication site might include characteristic substances associated with working plutonium metal ‘‘buttons’ into raw shapes before machining, such as tantalum, magnesium oxide, aluminum, graphite, calcium fluoride, plutonium, and plutonium oxide.[123]

NUCLEAR TESTING

Visible signs of nuclear tests

The Integrated Operational Nuclear Detection System (IONDS) aboard the Global Positioning System (GPS) satellites is designed to detect the

121 Tritium, a radioactive isotope of hydrogen produced mainly in nuclear reactors dedicated to that purpose, is a key element in advanced (boosted or thermonuclear) weapons as well as in accelerator-based neutron initiators. It is not subject to safeguards, however.

122 See Robert N. Thorn and Donald R. Westervelt, op. cit., footnote 74; and Paternoster, ‘‘Nuclear Weapon Proliferation Indicators and Observable,” op. cit., footnote 110, pp. 16.

123 John E. Dougherty, ‘‘A Summary of Indicators of Nth Country Weapon Development Programs, ’ Los Alamos Scientific Laboratory, Report LA-6904-MS, January 1978, p. 4.

Box 4-F-Iraq's Attempts to Conceal or Suppress Signatures

IAEA

IAEA inspector David Kay talks with Iraqi military authorities after they deny access to sites at Falluja in June 1991 in defiance of UN. Security Council Resolution 687.

Iraq successfully concealed both the size and level of progress of its nuclear program.[1] Four months after the June 1981 bombing by Israel of Iraq's Osirak reactor, Jaffar Dhia Jaffar (deputy minister of industry, head of reactor physics at Tuwaitha and now believed to have been the head of Iraq's nuclear weapon program) reportedly convinced Saddam Hussein that remaining in the NPT while embarking on a clandestine nuclear weapon program would present no serious difficulties.[2] Over the next decade, a nuclear program code-named Petrochemical-3 employed over 20,000 employees-7,000 of them scientists and engineers--at an estimated cost of $7 to $10 billion. This program included at least two major enrichment programs (EMIS and centrifuges, plus preliminary work with chemical enrichment), direct foreign technical assistance, and massive foreign procurement-much but not all of which fell within the domain of legal dual-use items. For example, so as not to arouse suspicion, the calutron program imported large iron-pole magnets(4.5 meters in diameter) from a European foundry in crude, unfinished form; such iron forgings were finished to specification in Iraq. The Iraqis obtained the design for buildings at the Ash-Sharqat nuclear facility that were planned to house calutrons by duplicating the Yugoslav-built Tarmiya site.[3]

Iraq did indeed have a major petrochemical industry, which helped provide cover for its nuclear-weapon-program purchases. However, at least three other factors also helped shield its foreign procurement of nuclear-related dual-use items from drawing too much attention. First, tensions among IAEA member states in the Middle East following the Israeli bombing of the Osirak reactor made it harder for the IAEA to be as proactive with respect to Iraq as it might otherwise have been.[4] Second, Iraq's war with Iran could arguably have been placing heavy demands on certain technologies that needed replenishment through imports. And finally, the United States

---

1 Much of the material in this box is based on discussions with David Kay, head of several IAEA nuclear inspections in Iraq carried out under the auspices of U.N. Resolution 687, and his presentation at the National Institute of Standards and Technology (NIST), Gaithersburg, MD, May 15, 1992.

2 David Kay, presentation at NIST, May 15, 1892, op. dt., footnote 1; from his discussion with Jaffar during one of the early IAEA inspections in 1991.

3 Jay C. Davis and David Kay, "Iraq's Secret Nuclear Weapon Program," *Physics Today*, July 1992, pp. 21-27.

4 Osirak was not yet operating at the time of the attack, but had already been placed under IAEA safeguards, which would have increased in scope once the reactor became operational. Furthermore, French technicians had been present at the reactor since 1978, and were scheduled to remain for years.

and other Western nations' tilt toward Iraq in the Iran-Iraq war gave Iraq many "green lights" for importing technologies that might otherwise have caused more concern?

The Iraqis also apparently had some success at foiling western National Technical Means (NTM) of verification. The Tarmiya site, for instance, which housed the main EMIS facility, had no security fence and no visible electrical capacity; only later did inspectors discover that it was powered by a 30-kV underground electrical feed from a 150 MWe substation several kilometers away. Tarmiya was also situated within a large military security zone, thereby needing no additional perimeter security or militarydefenses at the site.[6] At this same site, the Iraqis built a multimillion-dollar "chemical wash" facility for recovering uranium from refurbished calutron components. This facility was reportedly as sophisticated and dean as any in the West, and triple-filtered so as not to release any trace of effluents into the atmosphere that might have led to its detection once it began operation.

5 For instance, electron-beam welding machines were being imported under the justification of repairing tanks and jet engines. This explanation was accepted by western countries, despite the utility these machines had for certain nuclear technologies. A U.S. company also reportedly sold Iraq a sophisticated milling machine without its export-restricted laser-alignment module, but then suggested that the latter be purchased from the company's German subsidiary, where less-stringent export controls were in effect. David Kay, presentation at NIST, op. cit., footnote 1, May 15, 1992.

6 That the Tarmiya facility indeed housed a substantial piece of the Iraqi nuclear program was only confirmed after the Gulf War in the early summer of 1991, when the movement thereof large saucer-like objects (just prior to the first IAEA inspection of the site) led to the positive identification of the Iraqi calutron program. cf. Davis and Kay, "Iraq's Secret Nuclear Weapons Program," op. dt., footnote 3, p. 24.

characteristic double flash of light from above-ground nuclear tests anywhere in the world. Other kinds of satellite imagery might also be used to detect chilling equipment or surface changes associated with underground tests, possibly even changes caused by the shock waves from the test itself. [124]

Seismic signatures

If a country chooses to use underground nuclear explosive tests to further a weapon program, seismic disturbances would provide another telling signature. Nuclear tests with explosive yields above 10 kt in almost any region of the world would be very difficult to hide from existing seismic networks and other national technical means of verification. [125] Similarly, tests with yields down to about 1 kt would likely be detectable if there were a comprehensive world-wide network of seismic *stations* coordinated for the task.[126]

Much work has been done to analyze evasion techniques and the potential use of seismic waves to distinguish low-yield nuclear tests from earthquakes and chemical explosions. One evasion method is called "decoupling,' whereby explo-

124 For instance, the locations of nuclear explosion under Degelen Mountain in the Soviet Kazakhstan test site have been shown to be clearly visible through color changes associated with the shock-wave-caused spallation of rocks from the mountain above them. William Leith and David W. Simpson, "Monitoring Underground Nuclear Tests," in *Commercial Observation Satellites and International Security*, Michael Krepon, Peter Zimmerman, Leonard Spector, and Mary Umberger, eds., (New York, NY: St. Martin's Press, 1990), p. 115.

125 U.S. Congress, Office of Technology Assessment, *Seismic Verification of Nuclear Testing Treaties, OTA-ISC-361 (Washington* DC: *U.S. Government* Printing Office, May 1988), p. 13,

126 Ibid. For instance, with a system of tens of seismic stations distributed in and around the U.S. and former Soviet Union, nuclear tests in those countries with no attempt to muffle the seismic signals could be detected and identified down to 0.1-0,5 kt; similar coverage in the southern hemisphere or worldwide would require a corresponding worldwide seismic network. *Decoupled* explosions, or ones conducted in a large cavity to reduce the seismic waves they cause, could similarly be detected and identified down to yields of several kt to 10 kt. Also see Prof. Lynn Sykes, Lament-Doherty Geological Observatory, Columbia University, presentation at the conference sponsored by the IRIS Consortium, *The Proliferation of Nuclear Weapons and the Role of Underground Testing*, Princeton University, Nov. 12, 1992.

sions are carried out in large underground cavities.[127] However, preparations for decoupled tests might be observed by the amount of excavation required.[128] Another scheme involves hiding the signal of a nuclear test in the aftershocks of an earthquake. However, the seismic signals of earthquakes are known to differ in detectable ways from those of nuclear explosions, and exploiting them might require delaying a test detonation for weeks or longer, poised to explode within seconds of a suitable earthquake.[129] Successful evasion scenarios for nuclear tests, therefore, appear not to be very credible, especially for a nation with limited resources or experience in such areas.

Atmospheric releases from underground tests

Underground nuclear tests, even at sub-kiloton yields, generate radioactive gases at extremely high temperatures and pressures. Even under the best of circumstances, some of the radioactivity produced by underground explosions may still escape into the atmosphere through seepage or especially through controlled purges or ''drill-back' sampling to gather further data about the explosion. In the worst case, a massive 'venting' of the underground test would produce a plume of gas containing millions of curies of radioactive debris rising thousands of meters into the air.[130] Even if a country has considerable underground testing experience, massive releases can still occur; the ''Des Moines' test at the Nevada Test Site on June 13, 1962–-a test carried out in a tunnel about 200 meters into the side of a mountain-unexpectedly vented such an enormous cloud of debris (11,000,000 curies) that it reportedly caused a near-panic among test-site workers who rushed to drive away from a mountain-size radioactive cloud that formed above the test site and began blowing toward them.[131] Prior to this test, the United States had already accumulated experience from several dozen shaft or tunnel tests carried out at the Nevada Test Site in 1958 and 1961-62. If a clandestine test site in another country were suspected, and if timely access could be gained near the site, radioactive products could be monitored by aerial or ground sampling. Small amounts of specific gases produced by underground tests might also be detected at close range by exploiting their light-scattering properties when illuminated by lasers.

Nuclear-test-site preparation

Regardless of whether a country chooses to test a nuclear device at full yield or at reduced yields, a suitable underground site would be highly desirable. Since underground tests can be contained quite effectively when carried out properly, test-preparation activities would often be more observable than would atmospheric releases from tests themselves. **Drilling rigs,** sections of one-meter-diameter or larger pipe, mining operations, or road construction in new remote locations could all indicate such preparations and could probably be observed by reconnaissance satellites. (Determining that such activities actually do pertain to nuclear testing, however, may prove more difficult.) Contacts with foreign firms having experi-

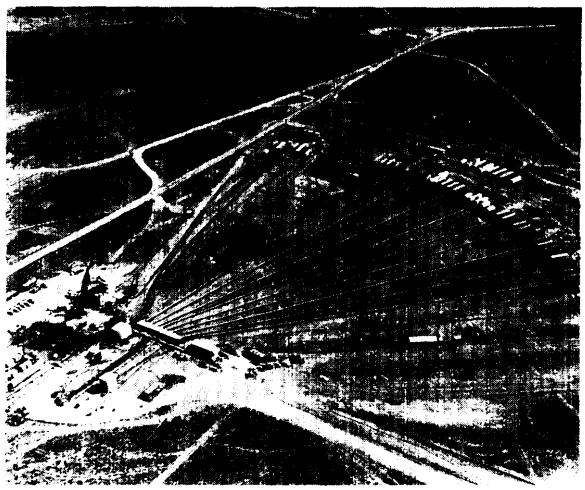
127 The possibility remains that decoupled tests below 1 to *2* kt would not be readily identifiable as nuclear tests, even if they could be monitored and detected by an enlarged worldwide seismic network. OTA, *Seismic Verification of Nuclear Testing Treaties,* op. cit., footnote 125, p. 14.

128 The diameter of the cavity needed to decouple a l-kt detonation in rock, for instance, is roughly 40 meters, and it sales as the one-third power of the yield, OTA, *Seismic Verification of Nuclear Testing Treaties,* op. cit., footnote 125, p. 100.

129 Distinguishing between earthquakes and nuclear tests depends somewhat on the strength of their seismic signals; fOr nuclear tests with yields below about 1 kt, discrimination can become very difficult.

130 U.S. Congress, Office of Technology Assessment, *The Containment of Underground Nuclear Explosions,* OTA-ISC-414 (Washington, *DC:* U.S. Government Printing Office, October 1989), p. 4, 33.

131 Jim Carothers, Office of History and Historical Records, Lawrence Livermore National Laboratory, presentation at the IRIS conference, Nov. 12, 1992, op. cit., footnote 126.


LAWRENCE RADIATION LABORATORY, LIVERMORE

Nevada test site location in 1966 prior to an underground nuclear test, Large drilling equipment, cranes, heavy electrical cables, and roads could all provide visual indicators of such a test site.

ence in large-hole drilling technology (for instance, through experience with nuclear testing programs in the United States or elsewhere) might also be indicators. Electronic data-acquisition systems, which are widely available around the world, would require extensive cabling systems suitable for transmitting diagnostic signals and might also be visible.

Deployment, Storage, and Maintenance of Nuclear Weapons

A country interested in possessing not just one or two but a small arsenal of nuclear weapons would have to make preparations for their storage, maintenance, handling, and deployment. Observable might include construction of maximum-security storage facilities or operational exercises reflecting the special requirements for handling nuclear weapons. Aircraft training runs for delivering nuclear weapons might exhibit unique flight profiles designed to give the pilot time to escape the effects of the blast. Military doctrine governing use of nuclear weapons would have to be developed and integrated into the command structure of appropriate forces. A greater number of people might thus learn of the weapons' existence, adding to the chance that human sources might reveal it.

The difficulty of producing fissile materials, however, limits the rate at which a proliferant could field nuclear weapons. If only a very small number of weapons were at hand, they might be reserved for strategic rather than battlefield use, thus reducing the need to conduct military exercises that anticipated combat in a nuclear environment. Furthermore, the weapons might be stored unassembled and their components kept at various locations. They might also be kept under the control of a small military or quasi-military unit outside of the regular military forces. It therefore might be very difficult to detect a nuclear force still in its infancy solely by relying only on observable changes in deployment, storage facilities, or military operations. Materials production would still provide the greatest opportunities for detecting such a program.

Appendix 4-A

Components, Design, and Effects of Nuclear Weapons

A nuclear weapon is a device that releases large amounts of explosive energy through extremely rapidly occurring nuclear reactions. Nuclear fission reactions occur when a heavy atomic nucleus is split into two or more smaller nuclei, usually as the result of a bombarding neutron but sometimes occurring spontaneously; fusion occurs when lightweight nuclei are joined, typically under conditions of extreme temperature and pressure. Nuclear weapons utilize either fission or a combination of fission and fusion.

A nuclear explosive device is normally made up of a core of fissile material that is formed into a ''super-critical mass' (see below) by chemical high explosives (HE) or propellants. The HE is exploded by detonators timed electronically by a "fuzing" system, which may use altitude sensors or other means of control. The nuclear chain-reaction is normally started by an "initiator" that injects a burst of neutrons into the fissile core at an appropriate moment.[1]

Fission devices are made with highly enriched uranium-235 or with plutonium-239, which is produced in nuclear reactors through neutron bombardment of uranium-238.[2] Uranium-233, which is produced in reactors fueled by thorium-232, can also be used to construct a fission device.

In fission weapons, energy is released through an explosive chain reaction that occurs when neutron-bombarded nuclei split and subsequently emit additional neutrons.[3] These additional neutrons sustain and multiply the process in succeeding fission reactions or ''generations. The minimum mass of fissile material that can sustain a nuclear chain reaction is called a *critical mass* and depends on the density, shape, and type of fissile material, as well as the effectiveness of any surrounding material (called a ***reflector or tamper)*** at reflecting neutrons back into the fissioning mass. Critical masses in spherical geometry for weapon-grade materials are as follows:[4]

	Uranium-235	Plutonium-239
Bare sphere:.	56 kg	11 kg
Thick U Tamper.	15 kg	5 @

[1] At a presentation at the South African Embassy, Washington, DC, on July 23, 1993, Waldo Stumpf, chief executive officer of the Atomic Energy Corporation of South Africa, Ltd., stated that South Africa designed a gun-type weapon using HEU that employed no neutron initiator.

[2] Uranium-235 is the only naturally occurring isotope that is ''fissile,'' "i.e., able to be fissioned by neutrons of any speed. Its concentration in natural uranium (most of which is uranium-238) is only about 0.71940.

[3] The amount of energy ultimately released is given by Einstein's relation $E=mc^2$, where c is the speed of light and m is difference in mass between the original nucleus and that of all the pieces into which it is spit.

[4] Robert Serber, *The Los Alamos Primer: First Lectures on How to Build an Atomic Bomb* (Berkeley, CA: Univ. of California Press, 1992), p. 33.

The "mushroom cloud" of hot gases and radioactive debris caused by a nuclear detonation near the ground can rise upwards of tens of thousands of feet and spread dangerous radioactive fallout far downwind.

Significant quantities of nuclear materials have been defined by the International Atomic Energy Agency (IAEA), which is charged with ensuring that these materials not be diverted from peaceful uses into weapons (see app. 4-C and table 4C-3 on significant quantities). These thresholds, which the IAEA considers sufficient for processing into a weapon, are 8 kg of plutonium (total element) or 25 kg of the isotope uranium-235 in highly enriched form (uranium containing 20 percent or more of the isotope uraniurn-235).[5] A first-generation fission weapon developed by a state without much experience at nuclear weapon design would most likely have a yield in the range of 1 to 50 kilotons.[6]

Two basic designs to assemble a supercritical mass of fissile material are *gun-assembly* and *implosion. In the* gun-assembly technique, a propellant charge propels two or more subcritical masses into a single supercritical mass inside a high-strength gun-barrel-like container. Compared with the implosion approach, this method assembles the masses relatively slowly and at normal densities; it is practical only with highly enriched uranium. (If plutonium—even weapon-grade-were used in a gun-assembly design, neutrons released from *spontaneous* fission of its even-numbered isotopes would likely trigger the nuclear chain reaction too soon, resulting in a ''fizzle' of dramatically reduced yield. See box 4-B on reactor-grade plutonium in main text.)

In the implosion technique, which operates much more rapidly, a shell of chemical high-explosive surrounding the nuclear material is designed (for example, by being detonated nearly simultaneously at multiple points) to rapidly and uniformly compress the nuclear material to form a supercritical mass. This approach will work for both uranium and plutonium and, unlike the gun-assembly technique, creates higher than normal densities. Since critical mass decreases rapidly as density increases (scaling as the inverse square of the density), the implosion technique can make do with substantially less nuclear material than the gun-assembly method.

In both types of designs, a surrounding *tamper* may help keep the nuclear material assembled for a longer time before it blows itself apart, thus increasing the yield. The tamper often doubles as a neutron reflector. In a fission weapon, the timing of the initiation of the chain reaction is important and must be carefully designed for the weapon to have a predictable yield. A neutron generator emits a burst of neutrons to initiate the chain reaction at the proper moment—near the point of maximum compression in an implosion design or of full assembly in the gun-barrel design.

Using these approaches, a substantial fraction of a weapon's fissile material would probably be blown

5 If one could assemble 8 kg of plutonium into a sphere, it would have a diameter of about 9.2 cm, somewhat bigger than a baseball; 25 kg of uranium would have a radius about 1.5 times larger.

6 A kiloton (kt) is defined as 4.18×10^{12} joules, which is approximately the energy released in the explosion of a thousand tons of TNT.

apart before it fissioned. To fission more of a given amount of fissile material, a small amount of material that can undergo fusion, deuterium and tritium (D-T) gas, can be placed inside the core of a fission device. Here, just as the fission chain reaction gets underway, the D-T gas undergoes fusion, releasing an intense burst of high-energy neutrons (along with a small amount of fusion energy as well) that fissions the surrounding material more completely. This approach, called *boosting,* is used in most modem nuclear weapons to maintain their yields while greatly decreasing their overall size and weight.

Fusion (or ''thermonuclear' weapons derive a significant amount of their total energy from fusion reactions. The intense temperatures and pressures generated by a fission explosion overcome the strong electrical repulsion that would otherwise keep the positively charged nuclei of the fusion fuel from reacting. In general, the x-rays from a fission "primary" heat and compress material surrounding a "secondary" fusion stage.[7] Such bombs, in theory, can be designed with arbitrarily large yields: the Soviet Union once tested a device with a yield of about 59 megatons.

EFFECTS OF NUCLEAR WEAPONS

The massive amounts of energy released by both fission and fusion explosives generate blast, heat, and radiation. Blast effects include shock waves, overpressure, and intense winds. Heat is released in the form of infrared and visible radiation which, for large-yield weapons detonated under the right conditions, can cause firestorms in cities well beyond the region of heavy blast damage.[8] Radiation effects include the prompt bursts of gamma rays and neutrons, the production of radioactive fission products and, if the explosion's fireball touches the ground, significant amounts of fallout of radioactive materials formed from or condensed upon soil that is swept up into the mushroom cloud.[9] Taking into account all of these effects except fallout, the *effective lethal radius*[10] for a l-kt fission weapon is approximately 0.7 km (area 1.5 km^2), for a 20-kt fission weapon 1.8 km (area 10 km^2), and for a l-Mt hydrogen bomb 7-13 km (area 150-600 km^2), depending on the occurrence of firestorms.[11]

---

7 The secondary usually contains solid lithium-6 deuteride. (Lithium-6 creates tritium when bombarded by neutrons produced during the detonation.) As in fission weapons, the liberated energy is reflected in the change in total mass during the reaction.

8 William Daugherty, Barbara Levi, and Frank von Hippel, "The Consequences of 'Limited' Nuclear Attacks on the United States," *International Security,* vol. 10, No, 4, spring 1986, p. 15.

9 A nuclear weapon detonated at high altitude can also generate a powerful pulse of radio waves (called "electromagnetic pulse' '), which can wreak havoc on some types of electronic equipment, but would not pose a direct human health risk.

10 Here, *effective lethal radius* describes a circular area around ground zero for which the number of people residing in the circle (assuming uniform population density) is the same as the total number of people that would be killed under normal conditions by the immediate effects of the explosion. Alternatively, it describes the radius at which the fatality rate, given a typical amount of shielding for an urban area, is approximately 50%.

11 See, for example, Dietrich Schroeer, *Science,* Technology, *and the Nuclear Arms Race (New* York, NY: John Wiley & Sons, 1984), p. 47 (figure 2.9).

Appendix 4-B

Enrichment Technologies

This appendix describes several approaches by which the uranium-235 isotope used in nuclear weapons can be separated from the more common uranium-238. Enrichment plants based on these approaches generally consist of a number of individual *stages*, each of which takes an input source of uranium, or "feed,' and produces two outputs: one with a greater concentration of uranium-235 than the feed (the "product"), and the other depleted in uranium-235 (the "tails"). The *separation factor* indicates how much enrichment each stage provides. (It is defined as the relative isotopic abundance of uranium-235 of the product divided by that of the tails.)

Tables 4-4 through 4-7 in the main text summarize and compare attributes of various enrichment approaches. The descriptions below are illustrative, but by no means exhaustive, of the isotopic enrichment methods known to have been supported by substantial research or development programs. Not included are many completely different techniques that have been proposed, some of which have undergone preliminary research.[1]

URANIUM AND ITS PROPERTIES

Several different chemical compounds of uranium are used in enrichment processes, all of which are difficult to handle. Although calutrons used by the United States during World War 11 and by Iraq in the late 1980s utilized UCl_4 feed to make ion beams, the most important feed material for enrichment is UF_6, a colorless solid at room temperature that sublimes at 56.5 "C. UF_6 is used in gaseous diffusion, centrifuge, aerodynamic, MLIS and, in its liquid state, thermal diffusion processes. It is highly corrosive to many metals and generally requires special nickel or aluminum alloys to process it. It also reacts violently with water and with many organic compounds such as oils and lubricants, so that handling systems must be extremely clean and free of leaks. Chemex processes (see below) normally use simple uranium compounds in hydrochloric acid solution.

In its elemental form, uranium is a silvery-white metal which, when finely divided in air, ignites spontaneously and, when in its atomic vapor state, is highly corrosive to many materials. AVLIS and plasma processes use atomic uranium. The ion beam

[1] Examples of some of the others can be found in Allan S. Krass et al., *Uranium Enrichment and Nuclear Weapon Proliferation* (London: Taylor & Francis, Ltd., 1983), pp. 171-2, 186-7, and references therein.

used in EMIS, though produced from UCI_4, is also elemental uranium.

THERMAL DIFFUSION

The uranium compound UF_6 in its liquid state is subjected to strong temperature differences to separate the heavier (uranium-238) isotope from the lighter one (uranium-235). The United States developed this process before WWII using concentric tubes, cooled on the outside wall by water and heated on the inside by steam; in the region between the tubes, the lighter isotope very slowly tended to concentrate near the inner wall and rise, whereby it was removed. The separation factor is no more than about 1.0003, and only very low enrichments are possible.[2] In 1944, 2,100 such tubes-each almost 15 m high-produced enrichments of only about 0.9 percent uranium-235 (starting from natural uranium with about 0.71 percent uranium-235) to feed the U.S. calutron program.[3] Thermal diffusion is not known to have been used on any significant scale since World War II.

GASEOUS DIFFUSION

UF_6 in its gaseous state is forced through a suitable porous barrier that preferentially passes the lighter molecules containing uranium-235, which travel on average a little faster and diffuse through the barrier slightly more efficiently. Gaseous diffusion is a proven technology, but requires an enormous amount of electricity to operate its pumps and compressors. Moreover, to produce significant quantities of enriched material, cascades must have thousands of stages, each stage having many elements or chambers. A cascade requires up to weeks between start-up and the point when it first produces appreciable amounts of enriched uranium (and months or longer to reach equilibrium). Therefore, 'batch recycling '—the process of reintroducing an enriched product as new feed stock into a cascade designed to produce LEU from natural uranium-is a relatively unattractive means of achieving higher enrichments. The U.S. gaseous diffusion plant at Oak Ridge made only a small contribution to the uranium enrichment effort during World War II, but the diffusion technology soon came to dominate the field.

GAS CENTRIFUGE

Precision high-speed rotors containing UF_6 gas spin within vacuum chambers. Heavier isotopes concentrate preferentially near the rotor's wall and are made to convect upwards, where they can be scooped out. New high-strength lightweight materials, such as carbon- or glass-fiber bonded with resins allow modem centrifuges to spin at extremely high speeds.[4] Cascade equilibrium times are measured in minutes to tens of minutes. This technology is widely used in several countries in Europe and in Japan, and has also been developed in the United States.

Attractive for proliferation in almost every respect (economical, efficient, widely dispersed proven technology, easily capable of high-enrichment, etc.), modern centrifuge technology is classified and is constrained by strict export controls.[5] Even so, Japan, Pakistan, India, and Brazil have each been able to build gas centrifuge cascades, and Iraq and South Africa had purchased many components in spite of export controls. All of these have been URENCO-type modern centrifuges, which are at least 20 times more productive than those designed by Gemot Zippe in the Soviet Union in the late 1940s. By the late 1950s, the Soviet Union adopted Zippe's basic design and went on to develop centrifuge technology to a production scale. (In 1942-43 during the Manhattan Project, the United States also considered using early-design centrifuges, but rejected them because of mechanical problems.)

---

[2] Separation factor is defined as ratio of the relative (uranium-235 to uranium-238) enrichment of the product stream to that of the tails or waste stream in any one stage of a cascade.

3 See Richard H. Rhodes, *The Making of the Atomic Bomb* (New York, NY: Simon & Schuster, 1986), pp. 552-4; and Manson Benedict and Thomas H. Pigford, *Nuclear Chemical Engineering, 2nd ed. (New* York, NY: McGraw-Hill, 1989), pp. 498-508. Even this small enrichment made a useful contribution to the productivity of the calutrons.

[4] Aluminurn and titanium rotors are only strong enough to run at moderate speeds; *maraging* steel—a particularly strong low-carbon alloy, typically consisting of at least 10% nickel plus cobalt, molybdenum, and other alloying agents-allows moderately high speeds. See Krass *et al., Uranium Enrichment. . . .* op. cit., footnote 1, pp. 132.

[5] Designs for low speed (subcritical) aluminurn-alloy centrifuges of the type developed by Gernot Zippe up to 1960, however, are an exception and are not classified.

AERODYNAMIC PROCESSES

A carrier-gas and isotope mixture is forced at high speed through a curved nozzle or vortex, allowing centrifugal force to concentrate the heavier isotopes nearer the outer portion of the flow where they can then be separated by a skimmer. Due to low separation factor (intermediate between gaseous diffusion and centrifuges) and high energy consumption, aerodynamic processes are economically not very attractive, but could be configured in modular cascades in a relatively small facility for a weapon program.

CHEMICAL EXCHANGE PROCESSES

Low-energy, low-maintenance chemical-exchange separation methods are based on chemical reactions that exhibit a slight preference for one uranium isotope over the other. Two methods known to have been developed to date are the Japanese Asahi ion-exchange process, which requires a proprietary resin, and the French solvent-extraction (Chemex) process. Both use special chemicals in the liquid state.[6] The Asahi process requires a specific catalyst and is limited by the mixing times of the reagents and the reticulated resin, but with the catalyst present the chemical exchange operates very rapidly. The French process does not require an exchange catalyst and is limited only by the mixing dynamics, but it must avoid impurities that can catalyze unwanted reactions. Because of the very low separation factor, up to thousands of stages can be required even to reach LEU; however, since a single physical item (e.g., an ion exchanger or pulse column) can contain tens or hundreds of effective "stages," these large numbers can be misleading. Both processes have been put through pilot-plant operations that have produced the expected enrichments at costs that would be economical on a commercial scale.[7]

In part because LEU made with chemical separation might permit other enrichment approaches to reach high enrichments more readily than they would if fed with natural uranium, France has offered to sell its Chemex process to countries only on the condition that they not pursue any other enrichment paths.

LASER PROCESSES

These methods include Atomic Vapor Laser Isotope Separation (AVLIS), Molecular-vapor Laser Isotope Separation (MLIS), and Laser-Assisted Processes (LAP) such as "Chemical Reaction by Isotopic Selective Activation" (CRISLA). All utilize small differences in the frequencies of light that atoms or molecules of different isotopic masses will absorb. Laser processes in general must induce several atomic or molecular interactions (excitations, ionizations, or chemical reactions) in succession, requiring several lasers to act in concert. Laser frequencies must be tuned very precisely-usually to an accuracy of about 1 part in 1,000,000.[8] Maintainin g such precise tuning at high power levels is one of several key technical obstacles faced by laser processes.

AVLIS, as developed at the Lawrence Livermore Laboratory, uses laser radiation to selectively strip an electron off atoms of uranium-235, but not uraniurn-238, in a uranium metal vapor at high temperatures and low density. MLIS uses tuned laser light analogous to AVLIS to selectively excite an electron in ^{235}UFG (but not ^{238}UF molecules and then to remove one fluorine atom. CRISLA's inventors claim that they have a proprietary compound that functions as an intermediary, selectively reacting with laser-excited $^{235}UF_6$ molecules. (This has not been independently confirmed, however.) Although MLIS and CRISLA reaction rates are both hindered by unwanted molecular collisions competing with desirable laser-excitation processes, the CRISLA process may have the added complexity of needing a particular collisional excitation to win out over the others.

Laser processes are still in development, and tests so far have been conducted only in the laboratory or in small pilot-plants. Because of their potential to produce high enrichments in a single step and their low energy use, they could eventually prove to be very efficient. Some of the equipment associated with laser processes is not subject to export controls and could probably also be developed-at least on a laboratory scale-by countries such as Israel, India, and Brazil.

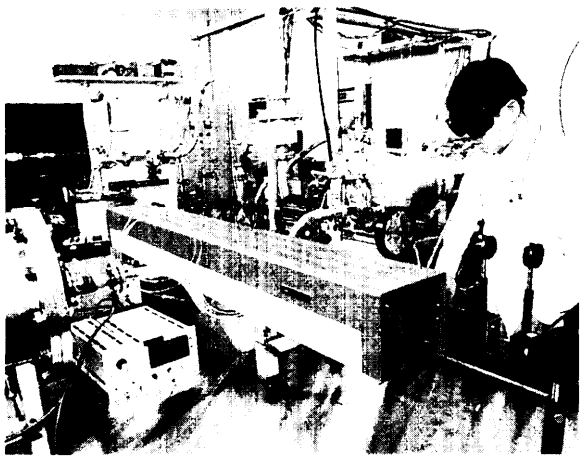
---

[6] If high enrichment levels are to be produced, great care must be taken to avoid the formation of a critical mass of material anywhere within the facility. Criticality with liquid and solid-phase methods is much more of a concern than with methods using gaseous forms of uranium.

[7] John M. Googin, senior staff consultant, Martin Marietta Energy Systems, Inc., private communication, Aug. 11, 1993.

[8] AVLIS uses pumped dye lasers, MLIS uses $C0_2$ infrared lasers and possibly xenon-chloride excimer lasers operating in the ultraviolet, and CRISLA uses CO infrared lasers.

PNC



Laser equipment that could be used for research and development of laser isotope separation (LIS) techniques. LIS methods are among several advanced technologies that may eventually lead to more efficient ways of enriching uranium.

Nevertheless, the required laser and material-flow technologies-especially at the scale needed for commercial operation—are highly sophisticated, and their integration poses a number of very serious difficulties.[9] However, in early 1992 the South African Atomic Energy Corporation announced that it was planning to begin operating one unit of a MLIS pilot enrichment facility in 1994, and a similar pilot-scale facility is being built in Japan. An AVLIS pilot plant is also under construction in the U.K.

ELECTROMAGNETIC PROCESSES

This group of technologies includes EMIS (calutrons), ion cyclotron resonance, and plasma centrifuge methods. Although theoretically as capable as laser processes at producing high enrichments with a small number of stages, these are — with the exception of the calutron—still in the experimental stage. All would require frequent maintenance, since the enriched product accumulates in collectors that can only be accessed when the system is turned off and partially disassembled. They also require a precisely controlled high-voltage vacuum-ion source (now subject to export controls under the 1992 Nuclear Suppliers Group dual-use guidelines) and strong, uniform electromagnets. (Ions are atoms with an electron removed, giving them a positive net electrical charge.) Ions of different masses are separated by exploiting the different curvatures of the paths they take when traveling through magnetic fields. Electromagnetic methods are also useful for separating plutonium isotopes, a task otherwise practical only through laser or centrifuge techniques.[10]

| Calutrons

Calutrons send high-voltage ions through a half-circle of rotation in a strong magnetic field inside a large disk-shaped vacuum chamber. They are very energy-inefficient, costly, bulky, and require a great deal of maintenance. Developed and used by the United States during World War II, their design was declassified decades ago.

Since higher separation factors require lower beam densities, up to several hundred calutrons could be required to produce enough HEU for a single bomb per year. However, use of even slightly enriched feed dramatically increases a calutron's production rate, thereby reducing the number of units needed. The Iraqi enrichment program relied primarily on calutrons.

| Ion Cyclotron Resonance

Ion cyclotron resonances techniques rely on the roughly 1 percent difference in frequency at which ions of different uranium isotopes orbit in a magnetic field. This difference allows precisely tuned radio waves to selectively energize one isotope over the other. The selected ions will absorb radio energy and orbit in ever larger spirals, eventually colliding with a downstream set of collector plates. Other isotopes are not affected, and most will pass through the gap in the plates. Key difficulties are that the process requires extremely

[9] For instance, between 1973 and 1990, the U.S. Department of Energy invested almost $1 billion in AVLIS development, but produced only kilogram quantities of 1% enriched uranium. In 1990 it had planned to build a 100,000-250,000 SWU/yr pilot plant that might have begun operation in 1992, but the idea has now been practically abandoned.

[10] The plutonium isotopes of interest are closer in mass than uranium isotopes and hence harder to separate.

Iraqi electromagnetic isotope separation (EMIS) equipment, here being uncovered by IAEA and United Nations inspectors, had been hidden in the desert following the Persian Gulf War.

uniform magnetic fields, usually calling for superconducting magnets, and a suitable electromagnetic signal or wave. In large machines, producing ions from metallic uranium can also be problematic. This enrichment process has been demonstrated with modest size units, but is not projected to become commercially competitive.

| Plasma Centrifuge Separation

Plasma centrifuge separation, in contrast to ion cyclotron resonance, requires an ionized gas (or ***plasma)*** **to be** created that is dense enough to undergo frequent internal collisions. If injected perpendicular to a magnetic field, such a plasma will forma ring and rotate. As the isotopes to to equalize in velocity, the heavier isotopes will tend to concentrate toward the outer portion of the ring where they can be removed (analogous to gas centrifuges). This is probably the least developed of the electromagnetic methods, and may use substantially more energy and achieve a lower enrichment factor than ion cyclotron resonance. It may also suffer from instabilities and other operational difficulties.

Appendix 4-C

Safeguards and the Civilian Nuclear Fuel Cycle

As of the end of 1992, there were 424 commercial nuclear power reactors in operation in 29 countries, producing 330 GW of electricity (see table 4C-1).[1] About 75 percent of these are light-water reactors (LWRs) fueled by low-enriched uranium (LEU) containing 3 to 4 percent uranium-235. Most of the remainder are fueled by natural uranium and are moderated by either heavy water (CANDU-type reactors) or graphite.[2] Some LWRs in France, Germany, and Switzerland have now been loaded with mixed plutonium-uranium oxide (MOX) fuel, which replaces about a third of their cores. (Japan and Belgium also have plans to fuel LWRs with MOX.) Several breeder reactors fueled by plutonium have also been built, but the majority of them have been shut down in recent years.

The low-enriched or unenriched fuel supplying almost all of these reactors is not a direct proliferation threat. However, all nuclear reactors are theoretical sources of material for nuclear weapons, since plutonium is produced in reactors fueled by uranium, and the fresh low-enriched fuel used in LWRs would be considerably easier than natural uranium to transform into HEU.[3] *If not adequately safeguarded, the* fuel cycle and facilities associated with power reactors provide a number of points from which relevant materials could be diverted.

So far, no nuclear facilities under full-time IAEA safeguards are known to have produced fissile material used in nuclear explosives. The five nuclear weapon states have each used dedicated facilities to make weapon materials. The several states thought to have prepared weapon-usable material outside or in violation of safeguards commitments have primarily used either small reactors coupled with unsafeguarded pilot reprocessing plants (e.g., India, Israel, and North

[1] These figures do not include 72 reactors under construction in these plus another three countries, or any research reactors—of which there are about 325 in over 50 countries. Half of these research reactors are in the five nuclear weapon states. The number of power and research reactors has remained nearly constant since the middle 1980s, with slightly more reactors having been decommissioned or shut down since that time than brought online.

[2] The moderator in a nuclear reactor slows down the neutrons produced in fission reactions so that they can more efficiently induce subsequent fission reactions.

[3] Uranium-233 (another weapon-usable material) is produced in reactors that contain thorium, but few reactors based on a thorium fuel-cycle have ever been built.

Table 4C-1-Nuclear Power and Research Reactors Around the World

	Power reactors in operation[a]			Power reactors under construction.		
	No. units	Total MW(e)	%electric power	No. units	Total MW(e)	Research reactors[c]
Argentina	2	935	19.1 %	1	692	5
Belgium	7	5,484	59.3%	—	—	5
Brazil	1	626	0.6%	1	1,245	4
Bulgaria	6	3,538	34.00/0	—	—	1
Canada	21	14,874	16.4%	1	881	14
China	1	288	NA	2	1,812	12
Cuba	—	—	—	2	816	0
Czech Republic	4	1,632	28.7%	2	1,784	2
Finland	4	2,310	33.3%	—	—	1
France	56	57,688	72.7%	5	7,125	20
Germany	21	22,559	27.6%		—	25
Hungary	4	1,729	48.4%	—	—	3
India,	9	1,593	1.8%	5	1,010	6
Iran. .,	—	—	—	2	2,392	2
Japan	44	34,238	23.8%	9	8,125	18
Kazakhstan,	1	335	NA	—	—	3
Korea, Rep. of	9	7,220	47.5940	3	2,550	3
Lithuania	2	2,760	NA	1	1,380	—
Mexico	1	654	3.6%	1	654	4
Netherlands	2	504	4.9%			2
Pakistan	1	125	0.8%	—	—	2
Romania	—	—	—	5	3,155	2
Russian Federation	28	18,893	11.8940	18	14,175	20
South Africa	2	1,842	5.9%	—	—	1
Slovak Republic	4	1,632	28.7%	4	1,552	2
Slovenia	1	632	34.6%	—	—	0
Spain	9	7,101	35.970			0
Sweden	12	10,002	51 .6%			2
Switzerland	5	2,952	40.0%	—	—	4
United Kingdom	37	12,066	20.6%	1	1,188	11
Ukraine	15	13,020	NA	6	5,700	2
Us.	109	98,796	21.770	3	3,480	92
World total:	424[d]	330,918[e]	NA	72	59,716	~326

NA = not available

a Data, which reflect the status as of the end of 1992 as reported by the IAEA, are preliminary and subject to change.

b percentages are for 1991, except for Russia and Slovenia, where preliminary 1992 data are used.

c Research reactors in operation as of May 1991. Total includes one research reactor in operation under the Commission of European Communities, five in Taiwan, plus the following (in countries that have no power reactors) : Algeria (1); Australia (2); Austria (3); Bangladesh (1); Chile (2); Colombia (I); Denmark (2); Egypt (I); Estonia (2); Greece (2); Indonesia (3); Iraq (2); Israel (2); Italy (6); Jamaica (1); Latvia (I); Libya (I); Malaysia(I); North Korea (2); Norway (2); Peru (2); Philippines (1); Poland (3); Portugal (1); Thailand (1); Turkey (2); Uzbekistan (1); Venezuela (1); Vietnam (1); and Zaire (1).

d Represents the average 1991 value for the Czech and Slovak Republics

e The total includes Taiwan, where six reactors totalling 4,890 MWe are in operation, accounting for 37.80A of the total electricity generated there in 1992.

SOURCE: *IAEA Bulletin, vol. 35,* No. 1, March 1993 and vol. 33, No. 3, September 1991; and William C. Potter, Nuclear *Profiles of the Soviet Successor States* (Monterey, CA: Monterey Institute of International Studies, May 1993).

Table 4C-2—Number of Installations Under IAEA Safeguards or Containing Safeguarded Material as of Dec. 31, 1992

Type of installation[a]	INFCIRC/153b (Corr.)	INFCIRC/66[c] (Rev. 2)	In NWS[d]	Total
Power reactors	182	17	2	201
Research reactors and critical assemblies	145	22	2	169
Conversion plants	7	3	0	10
Fuel fabrication plants	34	9	1	44
Reprocessing plants	5	1	0	6
Enrichment plants	5	1	1	7
Separate storage facilities	36	6	5	47
Other facilities	57	4	0	61
Subtotals	471	63	11	545
Other locations	468	32	0	500
Nonnuclear installations	0	3	0	3
Totals	939	98	11	1048

a For some types of installation, predominantly reactors and so-called "other locations," several installations can be located at a single site or facility.
b Covering safeguards agreements pursuant to NPT and/or Treaty of Tlatelolco; excludes locations in Iraq.
c Excluding installations in nuclear-weapon States; including installations in Taiwan, China.
d Nuclear-weapon States.

SOURCE: IAEA, *The Annual Report for 7992,* GC(XXXVII)/1060 (Vienna, Austria: International Atomic Energy Agency, July 1993), p. 149.

Korea) or unsafeguarded pilot enrichment plants (e.g., Pakistan, South Africa, and Iraq).[4]

The reason for the apparent preference for dedicated or unsafeguarded weapon facilities is straightforward: the construction and operation of nuclear power reactors and other commercial facilities so as to divert materials to a weapon program is neither the easiest nor the most efficient route to obtain nuclear weapon materials. First, more than 150 states have joined the NPT as nonnuclear-weapon states, which obligates all with nuclear facilities to sign and implement so-called *safeguard* agreements with the IAEA to provide assurance of *nondiversion* of nuclear materials. (As of Dec. 31, 1992, the IAEA had 188 safeguards agreements in force with 110 states plus Taiwan.[5] See table 4C-2.) Second, the vast majority of the material in the commercial nuclear fuel cycle is not directly suitable

[4] See, for example, David Fischer and Paul Szasz, *Safeguarding the Atom: A CriticalAppraisal* (London: SIPRI, Taylor and Francis, 1985), p. 52; and Leonard S. Spector with Jacqueline R. Smith, *Nuclear Ambitions: The Spread of Nuclear Weapons, 1989-1990* (Boulder, CO: WestView Press, 1990).

[5] The 45 parties to the Nuclear Non-Proliferation Treaty with safeguards in force base their agreements on the IAEA document INFCIRC/153(Corrected)—' 'The Structure and Content of Agreements between the Agency and States Required in Connection with the Treaty on the Non-Proliferation of Nuclear Weapons." The 10 non-NPT states with safeguards in force base their agreements on INFCIRC/66/Revision.2 —"The Agency's Safeguards System" (1965, as provisionally extended in 1966 and 1968). (The term "INFCIRC" comes from ''Infomnation Circular.' In addition, some safeguards were applied in the five nuclear weapons states under voluntary agreements.

Some important non-NPT states have accepted IAEA safeguards (INFCIRC/66) on certain facilities, but rarely do these cover key nuclear facilities from a proliferation perspective. In order for the IAEA to determine nondiversion for a State as a whole, it must have *all* nuclear materials in a country's fuel cycle under safeguards, a situation called fill-scope *safeguards.*


PETR PAVLICEK, IAEA

IAEA Board room showing participants at an international advisory committee meeting. Membership in the IAEA since 1957 has grown to over 100 States.

for weapons and requires difficult additional steps, such as conversion, further enrichment, or reprocessing, to make it so. For instance, all handling of commercial spent fuel requires extensive shielding to protect workers from lethal doses of radioactivity. Furthermore, reprocessing of that fuel yields reactor-grade plutonium, which is less desirable than other fissile materials for making weapons. Finally, operating large commercial facilities in the obviously uneconomic way that would be required to maximize their ability to produce weapon material-such as with frequent fuel changes-would draw considerable attention whether safeguarded or not.

IAEA SAFEGUARDS

IAEA safeguards are a system of procedures for nuclear material accountancy, control, and verification that are implemented through agreements between the IAEA and individual countries. These procedures involve: record-keeping at facilities; reporting requirements for material transfers and inventories; standardized measurements and assays; containment and surveillance methods (using seals, cameras, and other recording devices); and regular onsite inspections by the IAEA. The objective of safeguards is the timely detection of diversion (or verification of nondiversion) of a *significant quantity* of nuclear materials from *declared peaceful* activities to nuclear explosive purposes (see tables 4C-3 and 4C-4). Except for the **possibility of so-called "special" inspections-which had not been used at any undeclared location prior to the Persian Gulf War—safeguards agreements require only that declared (peaceful) activities be verified as being peaceful, and that the materials they involve be accounted for; they do not require verification of the absence of nondeclared (possibly weapon) activities (though such activities, if discovered, would be a violation).** Furthermore, even strict adherence to safeguards cannot predict future intent.

NPT safeguards focus on nuclear materials themselves and not on other facilities that potentially *could*

Table 4C-3--IAEA Significant Quantities of Nuclear Materials

	Material	Significant quantity	Safeguards apply to?
Direct-use material:	Pu[b]	8 kg	Total mass of element
	U-233	8 kg	Total mass of isotope
	U (with U-2352 20%)	25 kg	Mass of U-235 contained
Indirect-use material:	U (with U-235 < 200/0)'	75 kg	Mass of U-235 contained
	Thorium	20 tonnes	Total mass of element

a Plus rules for mixtures, where appropriate.
b For plutonium containing less than 80% Pu-238.
c Includingnatural and depleted uranium.

SOURCE: *IAEA Safeguards Glossary, 1987 Edition*, IAEA/SG/INF/1 (Rev. 1), (Vienna, Austria: International Atomic Energy Agency, December 1987), p. 24.

Table 4C-4-Estimated Material Conversion Time for Finished Plutonium- or Uranium-Metal Components

Conversion time	Beginning material form
Order of days (7-10):	Pu, HEU, or U-233 metal
Order of weeks (1-3)[a]:	PuO_2, $Pu(NO^-_3)_4$, or other pure Pu compounds;
	HEU or U-233 oxide or other pure U compounds;
	MOX or other nonirradiated pure mixtures containing Pu and U (U-233 + U-2352 20%); or
	Pu, HEU, and/or U-233 in scrap or other miscellaneous impure compounds
Order of months (1 -3):	Pu, HEU, or U-233 in irradiated fuel
Order of one year:	U containing < 20% U-235 and U-233; or
	Thorium

a This range is not determined by any single factor, but the pure Pu and U compounds will tend to be at the lower end of the range and the mixtures and scrap at the higher end.

SOURCE: *IAEA Safeguards Glossary, 1987 Edition,* IAEA/SG/INF/1 (Rev, 1), (Vienna, Austria: International Atomic Energy Agency, December 1987), p. 24.

be used to process them.[6] Materials are safeguarded at many stages in the fuel cycle: conversion (where uranium concentrate or plutonium, if it has been separated for use in fuel, may be cast into its fluoride, oxide, metal, alloy, nitride, or carbide forms); enrichment; fuel fabrication; reactor operation; spent-fuel storage; and reprocessing. The earliest phases of the fuel cycle, however, are not subject to safeguards. These phases involve mining the raw uranium-containing ore and "milling" it to convert it into natural-uran"urn concentrate (U_3o_8) called *yellowcake (see* figure 4C-1).

Few countries operate facilities that represent all stages of the fuel cycle, and some may have only a single nuclear research reactor supplied and fueled by another country. Nevertheless, unsafeguarded facilities could, in theory, be operated clandestinely along with safeguarded ones at any of these stages. Under safeguards agreements for non-NPTcountries (INFCIRC/66), only certain facilities and materials are subject to safeguards; these states can legally operate other, undeclared facilities, and process undeclared material obtained from either their own uranium deposits or from other non-NPT states, outside of safeguards.

In nonweapon-state NPT parties, however, the requisite INFCIRC/153 safeguards agreements do not permit *any* nuclear facilities to be undeclared, even if they were to use only indigenously produced materials. Furthermore, in only one circumstance-which has never occurred-may such a state be permitted to transfer safeguarded material to a nonsafeguarded nuclear facility.[7]

The safeguards process consists of three stages (see figure 4C-2):

- *examination by the IAEA of state-provided information,* which covers design of facilities, inventories, and receipts for transfers and shipments of materials;
- *collection of information by IAEA inspectors,* either to verify material inventories, operating records, or design information or, in special circumstances, to clarify unusual findings; and
- *evaluation by the IAEA* of this information for completeness and accuracy.[8]

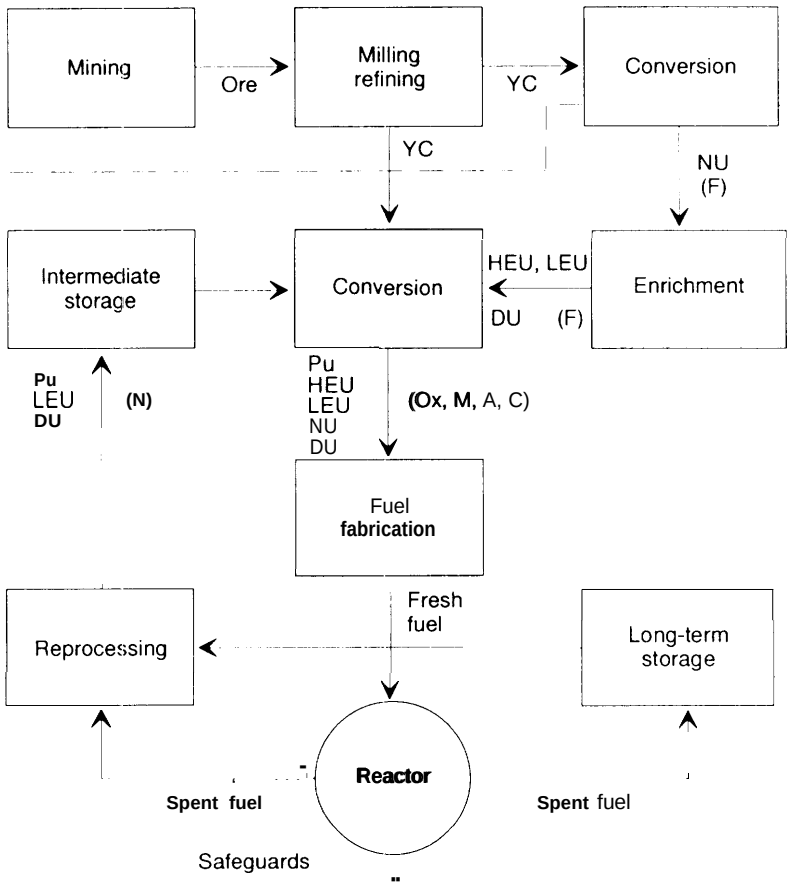
Taking into account each country and facility under safeguards, the IAEA annually produces a Safeguards Implementation Report (SIR) that contains qualitative judgments on whether safeguards goals have been fulfilled. However, these reports are not made available except to the IAEA Board of Governors and member governments.

6 Facilities that are built *with the express purpose of eventually containing nuclear materials,* however, must be declared.

7 This exception covers the temporary removal of a declared amount of material from safeguards to a *declared (nonnuclear weapon) military* facility, such as for submarine propulsion reactors.

8 See, for example, *IAEA Safeguards: An introduction (Vienna:* International Atomic Energy Agency, **1981), p. 19. Any** discrepancy of nuclear materials between the recorded (book) inventory and the physical inventory determined by inspections is called *material unaccounted for* (MUF). When MUF exceeds the amount attributable to measurement uncertainties, the possibility of diversion exists and must be resolved, For an extensive discussion of safeguards concepts and methodologies, see also Fischer and Szasz, *Safeguarding the Atom,* op. cit., footnote 4; and Lawrence Scheinman, *The International Atomic Energy Agency and World Nuclear Order* (Washington, DC: Resources for the Future, 1987), especially chapters 4 and 5.

Figure 4-Cl-Simplified **Flow Diagram of the Nuclear Fuel Cycle**

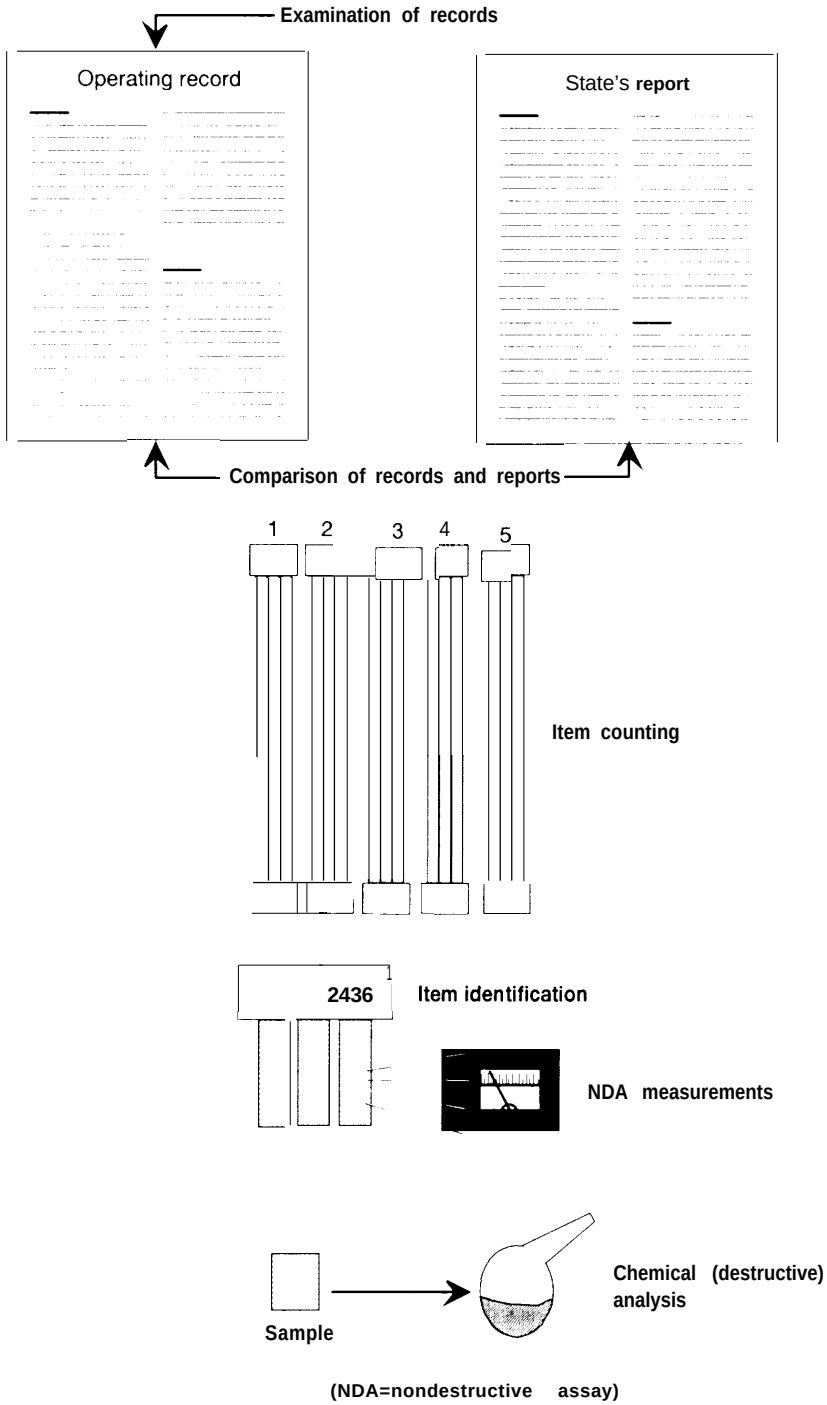


SOURCE: *IAEA Safeguards: An Introduction,* IAEA/SG/INF/3 (Vienna: International Atomic Energy Agency, 1981), p. 17.

Before Iraq was shown to have violated safeguards, no safeguards disputes had ever been referred to the U.N. Security Council. Since then, the possibility of Security Council action has been raised with respect to compelling North Korea to allow inspections of two sites suspected of containing nuclear waste. Despite its NPT obligations eventually to do so, North Korea also had still not shut down one of its reactors (as of the summer of 1993) so as to allow IAEA inspectors to examine its core. Such inspections are necessary to determine whether North Korea has ever produced significant quantities of plutonium.

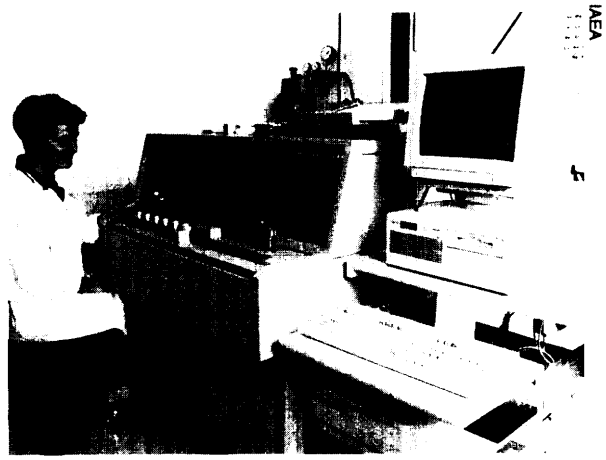
For reactors and fuel storage areas, material accountancy consists of identifying and counting fuel rods and assemblies and verifying their composition using nondestructive assays (NDA). LWR fuel assemblies are enclosed in the reactor vessel in such a way that the reactor must be shut down to change fuel

Figure 4-C2-Verification Activities of IAEA Inspectors or of the Safeguards Analytical Laboratory



SOURCE: *IAEA Safeguards; An /introduction,* IAEA/SG/INF/3 (Vienna: International Atomic Energy Agency, 1981), p. 23.

IAEA safeguards inspectors (center) checking fresh fuel elements at a nuclear power plant. At such facilities, safeguards focus on item identification and material accountancy, in part by verifying the records of plant operators.



X-ray fluorescence spectrometer, which supports one of the techniques used by the MEA to analyze samples taken during nuclear inspections.

elements. This shutdown is time-consuming and observable and makes the design and implementation of safeguards for LWRs particularly simple.

CANDU-type heavy-water- moderated natural-uranium reactors, and Soviet RBMK-type graphite-moderated reactors, however, are refueled by inserting new fuel rods while simultaneously removing old ones—a process that does not require shutting down the reactor. Safeguarding such reactors requires much more frequent inspections as well as specialized equipment (e.g., automated bundle counters) to inventory the replacement of fuel elements. Furthermore, since heavy water reactors (HWRs) can be refueled much more inexpensively and easily than other types of reactor, fuel can be cycled through them quickly. Such reactors are therefore better suited than many others to produce weapon-grade plutonium[9] (see box 4-A in main text).

Once plutonium is separated, it represents much more of a proliferation hazard than when it is bound up within radioactive spent fuel. If reprocessing is done at a distant site, or separated plutonium is subsequently transferred to a MOX fuel-fabrication facility or back to the country of origin, the transport of spent fuel and especially of separated plutonium represent vulnerable points in the fuel cycle for diversion or theft.

At "bulk-handling" facilities (such as those for enrichment, fuel fabrication, and reprocessing), samples of material from within *material balance areas* must periodically be removed and taken to an IAEA laboratory to determine their composition. The uncertainties in measurement at large bulk-handling facilities are necessarily much larger than those **involving the discrete items most often associated with reactors and their fuel.** (Consequently, the IAEA inspects bulk-handling facilities much more often, sometimes stationing permanent resident inspectors at these sites. Almost 50 percent of the total inspection effort is expended at bulk-handling facilities, even though these represent only about 7 percent of the total number of installations under safeguards. [10])

Technologies for implementing safeguards improved dramatically during the 1980s, and with these improvements have come greater transparency and confidence that the international fuel cycle is not being used to aid proliferation. The IAEA has incorporated computerized inspection reporting systems and has improved various methods for taking measurements and implementing containment and surveillance tech-

---

g An unsafeguarded Canadian research HWR supplied the plutonium for the device India exploded in 1974, and a French-supplied HWR has been the source of unsafeguarded plutonium in Israel. Similar but *safeguarded* HWRs had been involved in suspect activities in South Korea and Taiwan before the U.S. persuaded these two NPT countries in the 1970s to abandon their reprocessing efforts.

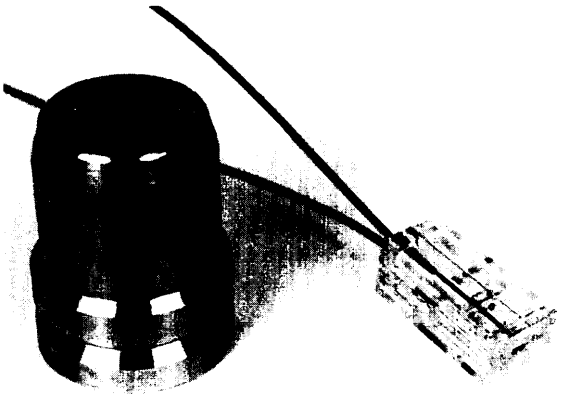
10 v. Schuricht and J. Larrimore, ''Safeguarding Nuclear Fuel Cycle Facilities,' *IAEA Bulletin, vol. 30, No.* 1 **(1988),** p. 11.

niques (see figure 4C-3), including methods for film processing, verification of seals, and analysis of gamma spectrometric data. New tamper-resistant surveillance television and recording systems have been installed in an increasing number of facilities.[11]

A number of improvements in IAEA safeguards and procedures have also been adopted since the 1991 Persian Gulf War. These include establishing earlier reporting requirements for nuclear plant-design information; taking steps toward more universal reporting of exports, imports, and inventories of nuclear materials and equipment; reaffirming the right to conduct special inspections; and accommodating the use of more diverse sources of information.

Nevertheless, the IAEA safeguards system has inherent limitations with respect to forestalling potential nuclear weapon programs, some of which are the following:

- it does not cover all states, or even all facilities and items that could be used by a nuclear weapon program in those states that are covered (for example, it makes no attempt to cover research and development on nonnuclear components of nuclear weapons);
- it does not prohibit states from acquiring stockpiles of weapon-usable material (plutonium and HEU), or the means to produce them, provided that stocks and facilities are declared and for peaceful purposes (the IAEA, in fact, is charged with assisting member states in the development of their nuclear fuel cycles);
- it suffers from inherent uncertainties at bulk-handling facilities;
- its access to sources of information remains limited;



IAEA

Two seals, known as COBRA and ARC, used by the IAEA to provide assurance that containers or other inspected items have not been tampered with between inspections.

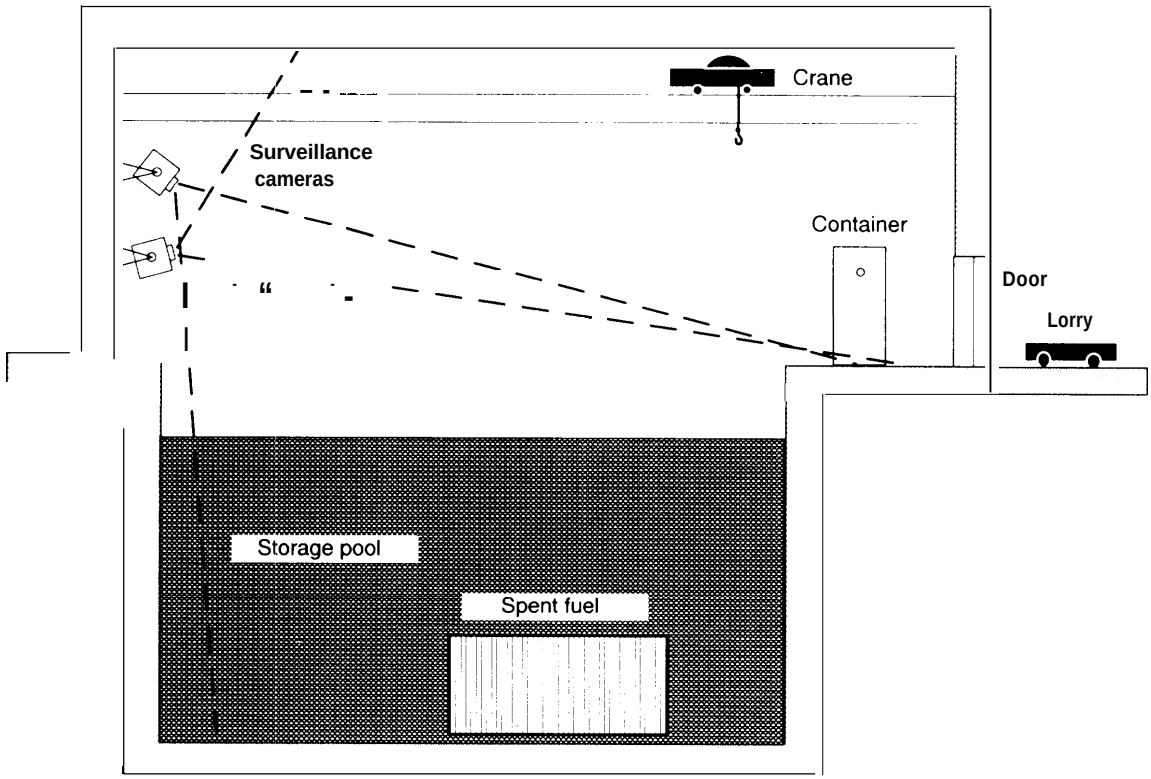
- it lacks an effective means of enforcement; and
- it is subject to diplomatic and political pressures to treat all states equally, making it difficult to select some as being of particular proliferation concern or to subject them to closer scrutiny. The bulk of the IAEA safeguards budget today is spent on facilities in Japan, Germany, and Canada, which are not regarded as countries of current proliferation concern.

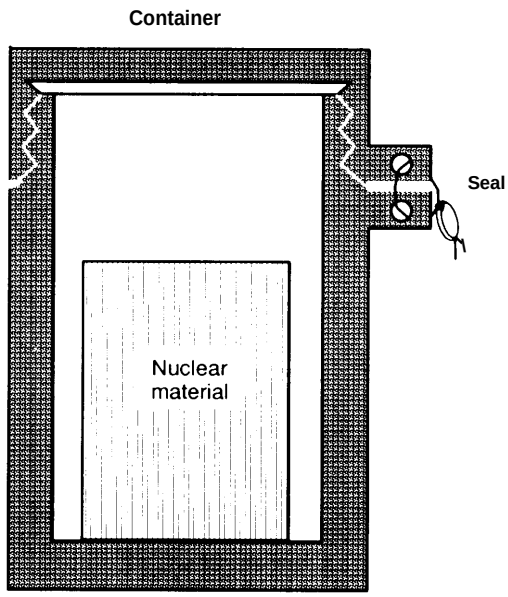
Policy options to strengthen IAEA safeguards and other aspects of the nuclear nonproliferation regime have been discussed in a number of recent articles[12] and will also be addressed in a subsequent OTA report on nonproliferation policies.

11 Other equipment that has been improved over the last decade includes bundle counters for reactor that are refueled while online, and various equipment for measuring composition and amounts of nuclear material, for example, portable multichannel analyzers, K-edge densitometers, electromanometers, Cherenkov viewing devices, and neutron coincidence counters.

12 See, for example, Lawrence Scheinman, "Nuclear Safeguards and Non-Proliferation in a Changing World Order," *Security Dialogue*, vol. 23, No. 4, 1992, pp. 37-50, and *Assuring the Nuclear Non-Proliferation Safeguards System (Washington DC: The* Atlantic Council, October 1992); three articles in *Disarmament, vol. XV, No. 2,* April 1992: Hans Blix, "IAEA Safeguards: New Challenges, " pp. 33-46; Ryukichi Imai, ''NPT Safeguards Today and Tomorrow, ' pp. 47-57; and Lawrence Scheinman, ''Safeguards: New Threats and New Expectations, ' pp. 58-76; and David Fischer, Ben Sanders, Lawrence Scheinman, and George Bunn, *A New Nuclear Triad: The Non-Proliferation of Nuclear Weapons, International Verification and the IAEA,* PPNN Study No. 3 (Southampton U.K.: Programme for Promoting Nuclear Nonproliferation, September 1992).

Figure 4-C3-Typical Containment and Surveillance (C/S) Measures Applied by the IAEA





SOURCE: *IAEA Safeguards: An Introduction,* IAEA/SG/INF/3 (Vienna: International Atomic Energy Agency, 1981), pp. *24-25,*

Appendix 4-D

Dual-Use Export Controls

Meeting in Warsaw from March 31 to April 3, 1992, the 27 members of the Nuclear Suppliers Group[1] approved a broad new set of export control guidelines pertaining to the transfer of nuclear dual-use items. They agreed that each of the NSG member countries would implement the guidelines by the end of 1992[2] and would adopt a common policy requiring the application of full-scope IAEA safeguards as a condition of arty significant new nuclear exports to nonnuclear weapon states.[3] The new guidelines include a technical Annex specifying 65 categories of nuclear-related dual-use equipment, materials, and technologies that are to be controlled, and establish procedures governing their transfer.

GUIDELINES AND LICENSING PROCEDURES

The new guidelines stipulate the following:

1. Licenses shall be required for the transfer of any item in the Annex to any destination by any participating country;

2. Transfers shall not be authorized:
   - if they are for use in a nonnuclear-weapon state in a nuclear explosive activity (including work on components or subsystems) or in an unsafeguarded nuclear fuel-cycle activity;
   - if there is an unacceptable risk of diversion to such an activity; or
   - if the transfers are contrary to the objective of averting the proliferation of nuclear weapons.

3. In judging whether these conditions are met, ***factors that*** *should be taken into account include,* but are not limited to:
   - an evaluation of the appropriateness of the end-use and of the material for that end use;
   - a country's past compliance history with safeguards and dual-use tech-transfer obligations;
   - whether governmental actions, statements and policies have been supportive of nuclear nonproliferation; and

[1] The 27 NSG states were: Australia; Austria; Belgium*; Bulgaria; Canada*; Czech and Slovak Federal Republics*; Denmark; Finland; France*; Germany*; Greece; Hungary; Ireland; Italy*; Japan*; Luxembourg; Netherlands*; Norway; Poland*; Portugal; Romania; Russia*; Spain; Sweden*; Switzerland*; United Kingdom*; and United States.* (Countries with asterisks have been members of the Nuclear Suppliers Group since it was formed in 1977.)

[2] The guidelines are published in IAEA INFCIRC/254/Rev. I/Part 2, ***Nuclear Related Dual-Use Transfers***, July 1992.

[3] See, for example, Roland Timerbaev, "A Major Milestone in Controlling Nuclear Exports," *Eye on* ***Supply, No. 6,*** spring 1992, pp. 58-65.

- whether the recipient has been involved in the past in clandestine or illegal procurement activities.

4. Before granting a License, a supplier shall be required to obtain a *statement of end-use and end-use location,* as well as a written assurance that the proposed transfer or any replica thereof will not be used in any nuclear explosive or unsafeguarded activity.
5. Supplier states shall be required to cooperate and consult with each other on licensing procedures, to report any *denials* of licenses, and to *refrain from licensing items whose export was previously denied by another supplier state.* (Exceptions and re-evaluations are allowed, however, with appropriate consultation,)

In sum, it is presumed that countries with insufficient nonproliferation credentials-even if party to the NPT—will be denied these dual-use goods.

ITEMS TO BE CONTROLLED

| Industrial Equipment

Combination spin-forming and flow-forming machines
- 2-axis, that can be fitted with numerical control units

Numerically controlled machine tools, control units, and software
- especially multi-axis ''contour-control' machining devices
- *except* that the precision and capability of these items must exceed a detailed set of technical specifications

High-precision (order of 1 micron) dimensional and contour inspection systems
- especially those capable of linear-angular inspection of hemishells

Vacuum or controlled-environment induction furnaces
- operating above 850 "C;
- *except if* for semiconductor wafer-processing

Isostatic presses
- capable of 700 atmospheres pressure with 6-inch or larger chambers

Robotic equipment (grippers and active tooling for ends of robot arms)

VADIM MOUCHKIN, IAEA

Portion of a remote manipulator that was destroyed in Iraq during an IAEA inspection in October 1991. Such manipulators can be used inside "hot cells" to handle radioactive material.

| able to safely handle high explosives or operate in radioactive environments and capable of variable/ Programmable movements
- *except if* for applications such as automobile paint-spraying booths

Vibration test equipment
- using digital control; 20-2,000 Hz; imparting forces of50kN(11,250 lbs) or more

Melting and casting furnaces-arc remelt, electron beam, and plasma
- generating temperatures above 1,200 degrees C in vacuum or controlled environments

▮ Materials

Aluminum alloys (of specified strength)
- in tubes or solid forms having outside diameters greater than 75 mm

Beryllium metal and alloys
- *except* beryllium metal windows for x-ray machines or beryllium oxides specifically designed as substrates for electronic circuits

Bismuth (of at least 99.99% purity)

Boron or its compounds (isotonically enriched in boron-10)

Calcium (high purity)

Chlorine trifluoride

Crucibles made of materials resistant to liquid actinide metals

Carbon or glass "fibrous and filamentary" materials of high-strength
- especially when in the form of tubes with 75-400 mm inside diameter

Hafnium and its compounds

Lithium isotonically enriched in lithium-6
- *except* lithium-6 incorporated in thermoluminescent dosimeters

Magnesium (high purity)

Maraging steel (of specified strength)
- *except* forms in which no linear dimension exceeds 75 mm

Radium-226
- *except* radium contained in medical applicators

Titanium alloys (of specified strength)
- in tubes or solid forms, with outside diameter greater than 75 mm

Tungsten and its compounds
- in amounts greater than 20 kg and having hollow cylindrical symmetry with inside diameter between 100 mm and 300 mm
- *except* parts specifically designed for use as weights or garoma-ray collimators

Zirconium and its alloys
- *except in* the form of foil of thickness less than 0.1 mm

| Uranium Isotope Separation Equipment and Components

Electrolytic cells for fluorine production (capable of 250 g of fluorine per hour)

Centrifuge rotor-fabrication andbellows-forming equipment

Centrifugal multiplane balancing machines (with specific characteristics)

Filament winding machines

Frequency changers (converters) or generators
- with specific characteristics, and operating from 600-2,000 Hz
- *except if specifically* designed for certain types of motors

Lasers, laser amplifiers, and oscillators
- copper-vapor and argon-ion lasers with 40 W average power
- high-pulse-rate lasers (tunable dye lasers, high-power carbon-dioxide lasers and excimer lasers)
- *except* continuous-wave or long-pulse-length industrial-strength CO_2 lasers for cutting and welding

Mass spectrometers and mass spectrometer ion sources , especially when lined with materials resistant to UF_6
- certain exceptions apply, however

Pressure measuring instruments, corrosion-resistant

Valves (special corrosion-resistant types using aluminum or nickel alloy)

Superconducting solenoidal electromagnets
- high magnetic field (greater than 2 tesla)
- with inner diameter greater than 300 mm and highly-uniform magnetic field
- *except if* specifically designed for medical nuclear magnetic resonance (NMR) imaging systems

Vacuum pumps (of specified size and capacity)

Direct current high-power supplies (100 V, 500 amps; e.g., for EMIS magnets)

High-voltage direct-current power supplies (20,000 V, 1 amp; e.g., for EMIS ion sources)

Electromagnetic isotope separators (EMIS)
- with ion sources capable of 50 mA or more

| Heavy-Water Production-Plant-Related Equipment (other than trigger list items)

Specialized packings for water separation

Specialized pumps for potassium amide/liquid ammonia

Water-hydrogen sulfide exchange tray columns

Hydrogen-cryogenic distillation columns

Ammonia converters or synthesis reactors

Implosion Systems Development Equipment

Flash x-ray equipment
- *except* if designed for electron microscopy or for medical purposes

Multistage light-gas guns/high-velocity guns (capable of 2 km,sec velocities)

Mechanical rotating mirror cameras (with recording rates above 225,000 fiarnes/see)

Electronic streak and framing cameras and tubes (with 50-ns resolution)

Specialized instrumentation for hydrodynamic experiments
- velocity interferometers for measuring 1 km/see in under 10 microseconds
- pressure transducers for 100 kilobars

Explosives and Related Equipment

Detonators and multipoint initiation systems
- electrically driven detonators (e.g., exploding bridge wires) capable of nearly simultaneous (2,5 microseconds) initiation over an explosive surface greater than 5,000 mm^2

Electronic components for firing sets
- switching devices or triggered spark-gaps (e.g., gas krytron tubes or vacuum sprytron tubes with 2500 V, 100 A, and delays of less than 10 microseconds)
- capacitors (kilovolt-level, low inductance)

Specialized firing sets and equivalent high-current pulsers (for controlled detonators)

High explosives relevant to nuclear weapons (e.g., HMX, RDX, TATB, HNS, or any explosive with detonation velocity greater than 8,000 rn/see)

Nuclear Testing Equipment and Components

Fast oscilloscopes (with 1 ns sampling or 1 GHz bandwidth)

Photomultiplier tubes (with large photocathodes and 1 ns time-scales)

Pulse generators (high speed; 0.5 ns rise-times)

Other

Neutron generator systems (for inducing tritium-deuterium nuclear reaction)

General nuclear-material and nuclear-reactor related equipment
- remote manipulators (used for radiochemical separation in "hot cells")
- radiation shielding windows (e.g., with lead glass, 100 mm thick)
- radiation-hardened TV cameras (able to withstand 50,000 grays)

Tritium, tritium compounds, and mixtures (containing more than 40 Ci of tritium)

Tritium facilities, or plants and components thereof (including refrigeration units capable of -250 "C)

Platinized carbon catalysts (for isotope exchange to recover tritium from heavy water, or to produce heavy water)

Helium-3
- *except* devices containing less than 1 g

Alpha-emitting radionuclides or their compounds (having alpha half-lives between 10 days and 200 years)
- *except* devices containing less than 100 mCi of alpha activity

STRENGTHS OF THE GUIDELINES

- A wide range of dual-use technologies and materials is subject to strict export controls. Implementation of these controls should create significant obstacles for a nuclear weapon program attempting to import the specified items.
- A large number of countries have pledged to abide by these guidelines by adopting them into their own export control laws and have agreed not to undermine control actions taken by others.
- Factors to be taken into account before export licenses are granted are not limited to a recipient country's being party to the NPT; these factors include past behavior and general compliance with nonproliferation goals.

POTENTIAL LIMITATIONS OF THE GUIDELINES

- Specific technical qualifiers and thresholds apply to the majority of controlled items on the list. A key questions is how effective each threshold is at determining the equipment's utility in a less-sophisticated or less-ambitions nuclear-weapon program -could dual-use items falling just short of the specifications still be helpful, and if so, how easily could they be obtained from NSG or non-NSG countries?
- The procedures only require reporting of license *denials. This* precludes routine active monitoring of trade, for example, to look for suspicious patterns of imports. However, the NSG has agreed to hold annual consultations for purposes including discussion on a voluntary basis of proposed and authorized transfers of these dual-use items.
- There is no provision for *inspecting the* end-use application, although individual countries may carry out such inspections on their own. (Inspections are periodically carried out, for example, by the Office of Export Enforcement of the U.S. Commerce Department.) This is primarily due to the expense and impracticality, both financial and political, of devising a comprehensive inspection regime for dual-use exports. If the guidelines are applied stringently, however, then export licenses for suspect proliferants will largely be denied, reducing the need for end-use inspections.