Introduction and Summary 1

Environmental monitoring is a potentially powerful supplement to current safeguards techniques intended to prevent the spread of nuclear weapons. Prior to the 1991 Persian Gulf War, the International Atomic Energy Agency (IAEA) administered safeguards primarily on the nuclear materials associated with known commercial or research facilities. Accounting for this material would provide notice were a proliferator to divert any to obtain the necessary nuclear fissile material for nuclear weapons.[1] Events in Iraq revealed after that war have demonstrated that such a safeguards approach addresses only part of the problem. Probably more important to halting proliferation is ensuring that countries do not violate their non-proliferation agreements by constructing covert facilities for nuclear material production. *Environmental monitoring,* which tests for the presence of materials that are likely to be emitted by such activities, can help inspectors detect undeclared activities at safeguarded sites and may be able to detect covert facilities at undeclared sites.

Environmental monitoring was first used by the IAEA in Iraq following the Gulf War. The agreement ending the war included the right for the United Nations to inspect all Iraqi nuclear facilities (declared and suspected) to determine if any nuclear-weapon related activities had occurred. The IAEA has a mandate from the United Nations Security Council to perform these inspections. In the month between the end of the war and the start of the inspections, Iraq removed much of the most incriminating equipment, such as the calutrons used for enrichment, and concocted stories to explain the remainder. Inspectors took samples of materials within and near facilities, and swipes of dust that had collected on the surfaces of equipment. These were analyzed at various laboratories, including in the United States. These analyses played a key part in demolishing Iraq's cover stories and exposing its nuclear weapon program, which included uranium enrichment and plutonium experimentation. The program had not been detected in earlier inspections despite the co-location of pro-

[1] For a review of the history of nuclear safeguards and the International Atomic Energy Agency that administers them, see: U.S. Congress, Office of Technology Assessment, *Nuclear Safeguards and the International Atomic Energy Agency*, OTA-ISS-615 (Washington, DC: U.S. Government Printing Office, June 1995).

totype facilities for the production of weapons materials with civilian, safeguarded facilities.

Subsequently, the IAEA used similar techniques in South Africa to provide additional assurance that all nuclear materials produced for its voluntarily terminated weapon program were fully accounted for. These techniques were also used to check the North Korean declaration of facilities and activities under the Non-Proliferation Treaty (NPT). The results from the application of these techniques, together with other information accumulated by inspection teams, led the IAEA to conclude that there were inconsistencies between the plutonium identified in North Korea's initial report and the reprocessing activities actually carried out.

The IAEA is now completing a series of field trials in cooperating member states to determine the efficacy of the techniques in a broad range of applications, and the Agency proposes to make environmental monitoring an integral part of the inspection process for safeguarding peaceful nuclear installations. The intent is to provide additional assurance that a country is not engaged in undeclared nuclear activity. Through this and other proposals, the IAEA is assuming a much more activist role in searching out any efforts to produce weapons.

This report analyzes how environmental monitoring works and what can be expected of it as part of safeguards. Chapter 2 reviews the emissions that can be expected from nuclear facilities that are supporting a weapons program. Chapter 3 looks at the techniques used for detecting those emissions, including sampling in the field and laboratory analysis. Chapter 4 reviews IAEA activities to implement environmental monitoring. Finally, chapter 5 looks at technologies now in the laboratory that could improve the effectiveness of environmental monitoring in the future. The remainder of this chapter provides a summary of the report and additional background.

MAJOR FINDINGS

- Use of environmental monitoring can significantly increase the ability of safeguards to detect undeclared nuclear activities at declared sites.
- Environmental monitoring is not a panacea and must be used in conjunction with other non-proliferation tools. However, some relaxation of conventional safeguards may be warranted as the new techniques are implemented in a broader, more integrated scheme.
- Technologies under development can significantly increase the chances of detecting and locating undeclared sites.
- Costs to the IAEA will be modest as long as efforts are focused on sampling in and around declared sites. Wide-area monitoring of the atmosphere to detect undeclared facilities would be very expensive. Wide-area monitoring of waterways appears more practical, but its application must be further investigated.
- The support of the United States and other member nations is essential to make the new techniques work. In addition to financial support to get the program moving, laboratory analysis, training of inspectors and IAEA laboratory staff, and research and development are needed.

NUCLEAR MATERIALS AND SAFEGUARDS

Many nations have the capability to develop nuclear weapons, though some would require considerable investment in facilities and manpower. The most difficult part of producing nuclear weapons is obtaining the fissile material (unless it can be stolen).[2]

[2] For a discussion of the technical requirements for making nuclear weapons, see U.S. Congress, Office of Technology Assessment, *Technologies Underlying Weapons of Mass Destruction*, OTA-BP-ISS-115 (Washington, DC: U.S. Government Printing Office, December 1993), chapter 4 ("Technical Aspects of Nuclear Proliferation") and especially appendix 4-A ("Components, Effects, and Design of Nuclear Weapons").

Nuclear explosives can be based on uranium or plutonium. Natural uranium can be found everywhere, but in order to be used in a weapon, it must be enriched. Natural uranium consists of three isotopes, uranium-238 (99.3 percent), uranium-235 (0.7 percent), and a trace amount of uranium-234. Only the uranium-235 can support a chain reaction, meaning not only that its nuclei can release energy by *fissioning*, or splitting, when struck by a neutron, but also that each fission releases sufficient neutrons to continue the process. Enrichment, an expensive and technologically difficult task, increases the concentration of uranium-235.[3] Fuel for light water power reactors must be enriched to about 3 to 5 percent uranium-235. A nuclear explosion cannot be achieved with less than 20 percent enrichment. For an effective weapon, the uranium-235 content must be much higher.

Alternatively, a proliferant can use plutonium, which is produced by irradiating uranium-238 in a nuclear reactor. Spent fuel from a conventional power reactor contains plutonium, but using it presents several difficulties (especially for the covert proliferator). Every country known to have produced a plutonium explosive has chosen to build a reactor whose primary task is the production of plutonium that is optimized for use in weapons.[4] In addition to a reactor, the proliferator needs reprocessing capability to extract plutonium from the irradiated uranium-238.

The NPT came into force in 1970 to provide a mechanism for nations to gain access to peaceful nuclear technology without giving rise to suspicions that they were using their facilities to produce weapon-related materials. Safeguards were instituted to check on their compliance as part of the treaty. Signatories to the NPT that had not tested a nuclear weapon before January 1, 1967 (i.e., all except the United States, the U.S.S.R. [now Russia], Britain, France, and China), pledged not to acquire nuclear weapons or to build nuclear facilities with unsafeguarded nuclear material. Only Iraq is known to have violated its commitments on a significant scale, but North Korea is not in compliance with its safeguards agreement with the IAEA because it refuses to accept certain activities identified by the Agency as necessary to assess the completeness of its declaration.

Most nations have signed the NPT. Exceptions include Israel, Pakistan, and India. Nonmembers are not legally bound to refrain from developing nuclear weapons or to accept safeguards on their facilities. However, essentially all nuclear exporters require all nuclear materials and critical nuclear-related equipment purchased by other countries to be placed under safeguards. Thus only indigenously developed facilities (and a few pre-NPT exports) are not safeguarded. Safeguards by themselves cannot stop proliferation. They only provide warning that a nation is not complying with its agreements. It is up to the United Nations and the international community to take action in response.

When a nation becomes party to the NPT, it is required to conclude a safeguards agreement with the IAEA, to declare all its nuclear materials, and to establish a system of controls for them. When the safeguards are implemented, each of the country's nuclear facilities must be specified (declared) in an attachment to the agreement. However, prior to the Gulf War, the IAEA did not verify the completeness of this declaration. Nor could it inspect undeclared facilities of non-members. It was never the IAEA's expectation that its efforts would deter all weapon programs, but it assumed that national intelligence programs would uncover covert efforts.[5] Iraq, North Korea, and South

[3] Uranium enrichment technologies are discussed in ibid., appendix 4-B ("Enrichment Technologies").

[4] For discussion of the use of "reactor-grade plutonium" and "weapon-grade plutonium" for nuclear weapons, see ibid., pp. 131–134.

[5] Bruno Pellaud, "Safeguards in transition: Status, challenges, and opportunities," IAEA Bulletin, vol. 36, No.3, 1994, Vienna, Austria, pp. 2–7.

Africa[6], three very different cases, showed that these assumptions could not be depended on in all situations.

There are several aspects to safeguards. The most prominent is materials accountancy, in which the total inventory of nuclear material in a country is monitored to ensure that none is diverted to weapon purposes. Besides measuring material inventories and material flows, inspectors check facility operating records to see if everything is consistent. In addition, there may be perimeter monitoring devices and cameras around critical areas to detect any undeclared removal of nuclear material.[7]

Consider the situation of an NPT signatory (or a country that has agreed to equivalent safeguards in order to import equipment) that decides to obtain nuclear weapons. It may have power reactors or research reactors, all of which would be under safeguards. Either might be used to produce fissile material, but the risk of detection under current safeguards is high. The country could abrogate its safeguards agreements and prevent IAEA inspectors from discovering that these facilities were being used for weapon purposes, but that would almost certainly end that nation’s ability to import nuclear fuel and equipment, and would probably precipitate international sanctions. A large commercial reprocessing plant (or enrichment plant) is far harder to safeguard effectively than a reactor used for research or for generating power, but no nation suspected of entertaining thoughts about proliferating is operating one under full-time safeguards.[8]

Therefore a potential proliferator is likely to favor a small reactor/reprocessing plant or an enrichment plant dedicated to the production of weapon materials even if it has a power reactor. IAEA inspectors do not typically have access to facilities not on their list, even to buildings right next door to ones they inspect regularly.[9] In fact, from the perspective of a proliferant state, co-locating legitimate and illegitimate facilities has several advantages. The peaceful facilities can provide some camouflage for the illicit activities, some personnel may work on both, and they can share utilities, security arrangements, and other functions.

To strengthen its safeguards system, including the ability to detect undeclared nuclear activities, the IAEA initiated Programme 93+2 in 1993. Environmental monitoring is a centerpiece of this effort, including field trials that are now being completed. The IAEA's Board of Governors endorsed the general direction of Programme 93+2 in its meeting March 27-30, 1995, and requested the Secretariat to prepare specific proposals for implementation.[10]

THE POTENTIAL OF ENVIRONMENTAL MONITORING

Modern analytical technology has made environmental monitoring an effective tool. A series of instruments has been developed that can identify extremely small traces of materials. Uranium and plutonium can be detected and identified by iso-

[6] The Iraqi program is discussed in chapter 3. North Korea apparently built its facilities prior to signing the NPT but has refused to declare and accept safeguards on all of them even though the IAEA discovered the others. South Africa dismantled its weapon program prior to signing the NPT. Since the NPT applies only to its members, neither it nor the IAEA can be faulted for the behavior of non-members. It is important to remember that the NPT, even though the primary international non-proliferation mechanism, is not capable of addressing the entire problem.

[7] The safeguards process is discussed in greater detail in U.S. Congress, Office of Technology Assessment, *Nuclear Safeguards and the International Atomic Energy Agency*, op. cit., footnote 1.

[8] India, not an NPT party, operates reprocessing facilities that are under safeguards only when reprocessing safeguarded spent fuel.

[9] The IAEA does have the authority to request so-called special inspections of any site if such inspections are necessary for the agency to fulfill its safeguards responsibilities. However, requesting a special inspection must be firmly based on information that the agency is unable to meet its safeguards obligations without access to specific named locations. This would be an extraordinary act that would not typically be done in the course of a routine safeguards inspection.

[10] IAEA Press Release, “IAEA Board of Governors Holds Spring Meeting, Considers Nuclear Safety Issues and Strengthening of Safeguards Verification System,” Mar. 31, 1995.

tope in less than nanogram quantities (a nanogram is one billionth of a gram; there are about 28 grams to the ounce). Particles as small as a micron (one millionth of a meter or about 0.000039 inches; the diameter of the period at the end of this sentence is about 350 microns) can be analyzed. Many instruments are sufficiently sensitive to detect the fallout of plutonium from above-ground nuclear bomb tests, almost all of which occurred more than thirty years ago.[11]

No industrial process can prevent minute traces of materials from escaping. Even the most sophisticated filtration systems can only reduce, not eliminate, releases. In particular, enrichment plants release traces of enriched and depleted uranium, including highly enriched uranium (HEU) for weapons if it is being produced. It is easy to distinguish isotopically altered uranium from natural uranium, and its presence is an indicator of enrichment activity (but not necessarily near where it is found). A detection of HEU where only natural or low enriched uranium should be is a clear warning signal that activities that could contribute to a weapons program are underway. Reprocessing plants release many fission products and other products as well as uranium and plutonium. Plutonium is entirely manmade, so its discovery in any significant quantity (i.e., at levels above those expected to be found from known atmospheric nuclear tests or other contamination) or with an isotopic composition inconsistent with a State's declaration is also a warning signal. Emissions are discussed in chapter 2.

These releases can be readily detected at levels that are far below those that pose hazards to human health. Tiny particles may settle out within process buildings or float out and be carried by the wind, sometimes for very long distances. Wherever they settle—on plants, in the soil, in waterways—they may be detected. Gaseous releases can be carried even further away, but dilution and varying wind patterns can make them harder to detect.

The first step in environmental monitoring is sampling: wiping surfaces in the facility with a cloth or tissue, or collecting leaves or other parts of plants, digging up soil, scooping up water, and other means of collecting material that has settled outside the buildings. Sampling is not particularly difficult in most cases, but the inspectors need training as to where to take the samples and how to avoid cross-contamination (from one sample to another, e.g., a trowel used to dig soil samples must be cleaned between each use, or particles from the first could give a false reading in the next sample).

The samples are then sent to a laboratory for analysis. Two general types of analysis are used—bulk and particle. Bulk analysis looks at the entire sample or a significant part of it. Analysis involves the application of many instruments such as mass spectrometers, which can separate isotopes of an element by their masses, allowing measurement of the relative abundance of the isotopes. Other instruments measure the emissions of radioactive decay to determine the radioisotope. Particle analysis selects individual particles, usually from the surface wipes, by examination under a microscope. Once isolated, the particle can be individually analyzed, using many of the same techniques. Particle analysis is more sensitive than bulk analysis because individual particle analysis can yield information on the precise formation of the particle, while bulk analysis averages the particles together. However, particle analysis also is significantly more expensive.

The IAEA's field trials involved sample collection at known nuclear facilities in various countries to explore the best ways to take samples and to determine the kind of information that could be gleaned from the analyzed samples. Facilities examined included enrichment plants,

[11] The United States, the Soviet Union, and the United Kingdom ceased testing nuclear weapons above ground when they signed the Limited Test-Ban Treaty in 1963. France continued atmospheric testing, at a level far below the pre-test-ban U.S. and Soviet rates, until 1975. China detonated the world's last above-ground nuclear test in 1980.

reactors, reprocessing plants, and research complexes. These tests have been completed, but public release of the results is contingent on the approval of the host country. Preliminary indications are that the field trials were generally successful. In most cases, the sampling was able to verify the declared activities at the facilities tested.[12] These activities sometimes could be detected several kilometers from the plant.

The IAEA believes that if environmental monitoring had been part of routine safeguards inspections in the 1980's, it would easily have revealed Iraq's weapons activities.[13] Of course, such monitoring would not necessarily have deterred these activities, because Iraq may not have co-located them with safeguarded activities that were subject to environmental monitoring had it known that this form of surveillance would take place. However, as noted above, separating weapon activities from legitimate nuclear activities would have significantly raised the costs and difficulty of the weapon program, and would perhaps have made it easier to detect covert facilities through other forms of surveillance.

The United States supported the IAEA field trials in several ways. Altogether, the U.S. financial contribution has been $6-8 million over 3 fiscal years.[14] Inspectors were trained; DOE's national labs did many of the bulk analyses; and the Air Force Technical Applications Center handled most of the particle analysis. The K-25 enrichment plant in Oak Ridge, Tennessee was one of the field trial sites. In addition, the United States is helping the IAEA design and construct a new clean lab for contamination-free handling and analysis of samples. Other IAEA members also supported the environmental monitoring program, and labs in many countries were used. Few if any other countries, however, can match the analytical precision of the U.S. labs, particularly for particle analysis.

In most cases, environmental monitoring will not produce a "smoking gun." Rather, it will supply information that must be combined with other sources to determine what activities have taken place. Thus it is a supplement to conventional safeguards, not a replacement. It could be an extremely important supplement, particularly if the IAEA is successful in obtaining access to sites and facilities related to the fuel cycle that are currently not available for investigation.

Implementing environmental monitoring may be controversial. The IAEA has determined that it has the authority to institute such monitoring at declared sites under agreements that have previously been negotiated with states with comprehensive safeguards agreements, but any change from current practices may alarm some countries even if they have no undeclared facilities. One problem is in the detection of plutonium and other radioisotopes. If sensitive environmental monitoring detects emissions from facilities claimed not to be emitting anything, public fears may be raised—even though the emissions may be far below levels that could threaten public health and safety. Furthermore, licensing difficulties may be encountered if any contamination is found in the area of a facility. Also, under some conditions, competitive information may be divulged, such as the operating conditions of an enrichment or fuel fabrication plant. Thus the nuclear industry in some countries may be concerned. On the other hand, the IAEA is used to protecting any proprietary information it has obtained under safeguards practices, and it would reasonably withhold any such information collected through environmental monitoring, assuming that no safeguards violations were found. Implementation must be done carefully and sensitively. One compensating factor is that the information may be helpful to the host state in meeting its own health and safety goals.

[12] Personal communication with International Atomic Energy Agency staff member, Mar. 31, 1995.
[13] Personal communication with International Atomic Energy Agency staff member, Apr. 4, 1995.
[14] Personal communication with Ira Goldman, U.S. Department of Energy, Jan. 11, 1995.

The field trials have demonstrated that costs to the IAEA of implementing environmental monitiring should be modest. Sampling can be done in conjunction with regular inspections. Environmental sampling requires personnel with only several days of training and relatively simple equipment. The lab analyses are more expensive than the sampling, especially for particle analysis. The data indicate that bulk analysis is probably adequate to detect undeclared activity at most facilities, and that with appropriate selection of samples to be tested, the costs will not be prohibitive.

In some cases, the IAEA may be able to reduce inspections when environmental monitoring is introduced. For example, if environmental monitoring confirms that a country is not operating a reprocessing plant, then inspection of spent fuel need not take place as often in order to provide timely warning of diversion.[15]

Wide area monitoring to detect undeclared facilities is much more problematic. Some materials can be carried long distances, either in the air or in waterways. Monitoring rivers is not difficult, and positive findings can be traced upstream. Furthermore, sediments often collect at various places, establishing a record of what has come downstream. The IAEA already is monitoring water in Iraq. However, it is relatively easy for a small, covert facility to minimize liquid runoff, and in dry areas there may not be sufficient rain to wash away and concentrate material that settles out from the atmosphere. Therefore, clear signals may not emerge. Effective air monitoring requires a great many stations, because a plume can follow an erratic pattern. These stations must be monitored frequently over an extended period if they are to catch a sporadic, short-duration plume, such as might result from the opening of a reactor or the reprocessing of a batch of fuel. Furthermore, all samples collected by these stations would need to undergo laboratory analysis. At a minimum, samples would have to be screened with a relatively low cost technique to determine if any require more precise analysis. Since the number of samples would be high, costs would be also. Hence air monitoring can be quite expensive.

Technology now under development should improve the capability to conduct environmental monitoring in several ways. Some will allow real-time, remote sensing. The Department of Energy's CALIOPE (Chemical Analysis by Laser Interrogation of Proliferation Effluents) Program, a collaborative effort at 5 national labs, is intended to produce instruments that can, from outside a site's perimeter, measure the constituents of a plume of emissions in the air. Real-time xenon and air particulate measurements are being developed by the Department of Energy. Other developments would increase the sensitivity of laboratory instruments, permitting the analysis of samples even more dilute than those that can be studied today. Portability of instruments is another goal so that inspectors can get an immediate indication of suspect isotopes or chemicals and monitor more intensively. Successful development of these projects should significantly improve the effectiveness of environmental monitoring. However, some of these projects may involve technology that cannot be given to the IAEA because of U.S. national security concerns.

If successfully implemented, environmental monitoring will be an important part of international non-proliferation efforts. In addition, it may prove to have a role in verifying the Comprehensive Test Ban Treaty and nuclear material production cutoff agreements.

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[15] Environmental monitoring will not detect a complete but unused reprocessing plant, nor any plans to send the spent fuel to another country for reprocessing. However, both these approaches probably would entail considerable delay and uncertainty in the procurement of plutonium relative to having a proven capability already.