CHAPTER 6

CAN THE IAEA SAFEGUARD FUEL-CYCLE FACILITIES? THE HISTORICAL RECORD

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INTRODUCTION

The peaceful use of nuclear power is premised on an international ability to prevent bomb-grade nuclear materials from going missing from civilian fuel-cycle facilities. This depends crucially on “safeguards” administered by the International Atomic Energy Agency (IAEA), which are supposed to detect any clandestine removal of a bomb’s worth of fissile material (or more) in time to prevent it from being manufactured into one or more nuclear weapons. Unfortunately, more than 4 decades after the creation of IAEA safeguards, considerable doubt remains as to whether the agency can attain this goal even at the relatively small number of existing fuel-cycle facilities, let alone at the many more such facilities envisioned as nuclear power expands globally.

Accordingly, this chapter assesses the current and anticipated efficacy of IAEA safeguards at civilian fuel-cycle facilities (also known as “bulk handling facilities”) and then formulates policy recommendations. The chapter starts by detailing the empirical record of safeguards shortfalls at such facilities. Second, it explains the two major risks of clandestine removal of fissile material from fuel-cycle facilities: diversion by states, or theft by sub-state insiders. Third, it details the scope of such facilities worldwide. Fourth, the chapter discusses the technical and political obstacles to achieving safeguards objectives, and various proposals to overcome them. Finally, the chapter concludes with policy recommendations based on the current and projected capabilities of IAEA safeguards.[1]

EMPIRICAL RECORD

Nuclear fuel-cycle facilities around the world, in states with and without nuclear weapons, have suffered accounting discrepancies entailing many bombs' worth of fissile material. This section first explores the record at such facilities in two nuclear-weapons states: the United Kingdom (UK) and France. Second, it illustrates the inadequacy of accountancy at such facilities under IAEA safeguards in two countries with varying levels of cooperation with the agency: Japan and Iran.

United Kingdom.

British Nuclear Fuels Limited's (BNFL) Sellafield site in northwest England includes a mixed-oxide (MOX) fuel facility, which operated from 2001 to 2011, as well as the Thermal Oxide Reprocessing Plant (THORP) that continues to operate. In 2005, an audit of the nuclear materials at the MOX facility revealed that the "material unaccounted for" (MUF) was 29.6 kilograms (kg) of plutonium, or roughly 3.5 "significant quantities" (SQ) of this fissile material, enough for several nuclear weapons. BNFL insisted that the figure did not mean that any material had been removed without authorization from its plants. The company asserted that its techniques to account for nuclear material followed internationally approved and recognized best practices. In particular, BNFL contended that the systems of statistical measurement and control at THORP were "the most advanced in the world."[2] However, on May 9, 2005, a BNFL inquiry revealed that a massive leak at THORP had gone undetected for 9 months. The leak occurred in a feed pipe to one of the two accountancy vessels, resulting in accumulation of 83.4 cubic meters of dissolver solution. This solution contained an estimated 19 metric tons of uranium and 190-kg of plutonium.[3] An accountancy tank is where the initial inventory of fissile material is measured for the purpose of establishing shipper-receiver differences (SRD). But the system failed to detect the increasing loss of material until 8 months after it began. To the credit of the plant's material accounting system, the first indications of the problem came not from any safety detectors (several of which were malfunctioning), but from the company's Safeguards Department, when it observed an anomalous SRD in March. Despite that, the leak was not uncovered until a month later.

In BNFL's review of the incident, the company commended the role of its Safeguards Department in detecting the leak, although acknowledging that the Nuclear Materials Accountancy system had not provided timely warning of lost material. The system "is intended to provide overall accountancy balances," and "is not designed to (nor is it intended that it should) be responsive to track material on a more real time basis." Later, BNFL recommended the introduction of "a nuclear tracking regime . . . with the objective of promptly detecting primary containment failure or misdirection of material."[4] This statement appears puzzling since BNFL had previously made claims, with the full support of the European Atomic Energy Community (Euratom), proclaiming the existence of near-real-time accountancy (NRTA) at THORP. For example, in a paper delivered at an IAEA safeguards symposium in 2001, a joint BNFL-Euratom team stated that: "Near Real Time Materials Accountancy (NRTMA) is fully operational in THORP, providing regular assurance of high quality material control."[5] In retrospect, this claim appears to have been exaggerated, at the least.

At the time of the incident, the plant was under Euratom safeguards. This institution has identical timeliness criteria as the IAEA for uncovering diversions of nuclear material (e.g., the detection of one SQ of direct-use fissile material within 1 month). However, Euratom failed to detect the MUF despite having access to the operators' accountancy records, as well as supposedly having access to process data, upon which it performed its own statistical tests.[6] Neither the plant operators nor the Euratom inspectors successfully detected the leak or sounded an alarm for 8 months—many times longer than the timely warning requirement. This incident suggests that even state-of-the-art safeguards cannot come close to satisfying the IAEA's explicit standards for detecting missing fissile material before it could be fabricated into a weapon.

France.

Along similar lines to the BNFL incident, the now closed MOX fuel facility in Cadarache, France, which operated under Euratom safeguards, encountered MUF situations twice during the last decade. This facility was operated from 1961 to 2004 by Cogema and then by Areva, which acquired Cogema. In

2002, the Euratom Safeguards Agency reported that "the annual verification of the physical inventory at Cogema-Cadarache plant in France found an unacceptable amount of material unaccounted for (MUF) on the plutonium materials [SIC]."[7] The problem was later attributed to the differences between measurement techniques by inspectors and operators, and to poor definitions of materials in historical accounting records. (If the latter were the issue, it is unclear why the MUF problem would not have arisen until 2002.) In September 2004, it was reported that Euratom finally had responded to Cogema's explanation of the 2002 MUF finding.[8] Thus, it took at least 2 years to resolve the discrepancy. Despite this explanation, the problems at the facility persisted.

In October 2009, the French Nuclear Safety Authority ordered the halt of decommissioning operations at the facility. When the facility had closed in 2004, its former operator, Areva, estimated that there would be a MUF of approximately 8-kg of plutonium due to holdup in the plant's gloveboxes—which are shielded hot cells along the process line in which technicians can remotely manipulate the nuclear material. However, 2 weeks into the cleanup of the facility, the French Atomic Energy Commission announced that it had already collected 22-kg and projected that the total might rise to 39-kg of MUF.[9] While the plutonium holdup might have accumulated in the gloveboxes over a long period of time, Areva's underestimation of the amount by almost five SQs suggests that the plant's accounting system failed and that the Euratom safeguards were insufficient to detect the potential diversion of several bombs' worth of fissile material. The repeated failure of safeguards in nuclear-weapons states to meet the IAEA detection standards, despite employing some of the most advanced accounting technologies in the world, raises serious questions about whether IAEA safeguards can achieve their objectives.

Japan.

Japan has boasted that it cooperates fully with the IAEA and applies the world's most advanced safeguards. Despite that, three of its fuel-cycle facilities have suffered substantial accountancy failures. This record raises serious concerns about the ability of safeguards to detect the diversion of fissile materials in a timely manner in any country.

At the Plutonium Fuel Production Facility (PFPF), a MOX fuel plant at Tokai-mura, the problem of residual holdup led to a significant material accountancy failure. Soon after the plant started up in 1988, operators noticed the problem of plutonium becoming stuck in gloveboxes. In response, the plant operator, Japan's Power Reactor and Nuclear Fuel Development Corporation (PNC), in conjunction with safeguards experts at the U.S. Los Alamos National Laboratory, designed a nondestructive assay (NDA) method to measure residual holdup *in situ*—that is, without dismantling the hot cells—known as the Glovebox Assay System (GBAS). However, the system's imprecision contributed to an overall measurement uncertainty of about 15 percent.

By 1994, the plant's MUF had grown to about 69-kg of plutonium. Because of the measurement uncertainty associated with the GBAS, even if the entire MUF were residual holdup, the IAEA could not exclude the possibility—with a confidence level of 95 percent, based on NDA measurements alone—that at least one SQ had been diverted. Consequently, the IAEA wanted PNC to cut open the plant's gloveboxes, remove the holdup directly, and measure it with destructive assay methods. PNC balked at this request, and the dispute remained unresolved until the Nuclear Control Institute—a Washington-based, nonproliferation advocacy group—publicly disclosed the existence of the discrepancy in 1994. After that disclosure, PNC agreed to shut down the plant, recover the holdup, install new equipment to reduce further holdup accumulation, and implement improved NDA systems to measure more accurately any future residual holdup. After an expenditure of $100 million to remove and clean out old gloveboxes and install new ones, PNC announced in November 1996 that it had reduced the MUF to less than 10-kg (but not less than one SQ). This partial resolution of the MUF issue took more than 2 years from the time the situation became public, which contrasts starkly with the IAEA's timely warning standard of 1 month for such fissile material that can be used directly to make a nuclear weapon.

Another long-unresolved MUF issue at Tokai was associated with the accumulation of plutonium-laden fuel scrap resulting from decades of MOX research and production activities at the site.[10] Press reports in the mid-1990s indicated that the scrap inventory at Tokai contained between 100- and 150-kg of plutonium.[11] However, much of this scrap was in an impure form that could not be accurately measured via NDA methods. An NDA instrument known as the Plutonium Scrap Multiplicity Counter (PSMC), developed by Los Alamos, was relatively effective for measuring pure scrap plutonium but much less so if the material was contaminated with moisture or light elements that could generate neutrons through (α,n) reactions. For heavily contaminated scrap, the measurement imprecision ranged from 10 to 50 percent, well above the 4 percent uncertainty cited by the IAEA as the international standard for scrap measurements.[12] Even with the PSMC's best case of 10-percent average imprecision, the uncertainty associated with measuring a scrap inventory containing 150-kg of plutonium would be greater than one SQ. Indeed, more than six SQs would have to be diverted to yield a 95 percent chance of detecting a diversion. Accordingly, the IAEA wanted the plant operator, PNC, to chemically purify the scrap and then use destructive assay to measure the plutonium more precisely. In 1998, the IAEA announced a formal agreement under which PNC would embark on a 5-year program "aimed at reducing the inventory of heterogeneous scrap material," which would be "gradually homogenized to allow enhanced verification, including destructive analysis."[13] No further information appears to be available on the status of this program, except for a brief mention in the IAEA 2000 Safeguards Statement of a containment and surveillance approach for the receipt and storage of MOX scrap at the "Solution Critical Facility" in Japan.[14]

The older reprocessing plant at Tokai also has suffered substantial material accountancy failures due to measurement and estimation errors, since it began operating in 1977. In January 2003, Japan admitted that the cumulative shipper-receiver difference—that is, the amount of plutonium that was estimated to have been shipped to the reprocessing plant in spent fuel minus the amount of separated plutonium that had actually been measured—was 206-kg, or about 25 SQs. This was nearly 3 percent of the total plutonium estimated to have been processed in the plant over its lifetime. A few months later, Japan revised its figures, claiming that the actual discrepancy was only 59-kg, because the remainder was either bound in the hulls of the spent fuel's cladding (12-kg), had been discarded with high-level liquid waste (106-kg), or had decayed into americium-241 (29-kg). However, it was unclear how figures as precise as these were derived, given the uncertainties inherent in measuring the plutonium in cladding hulls and in high-level waste, and in assessing the isotopic content of the spent fuel prior to reprocessing.

Japan's newest fuel-cycle facility is the larger, Rokkasho-mura Reprocessing Plant, which is now scheduled to commence commercial operations in 2016. Starting in the 1990s during design and construction, there was a massive multinational effort to develop and implement a state-of-the-art safeguards system at Rokkasho. Unfortunately, issues of cost and convenience played a major role in development of the safeguards approach and resulted in many questionable compromises. For instance, instead of having its own, independent, on-site analytical laboratory, the IAEA must share a laboratory with the facility operator, which raises the potential for tampering.

The IAEA itself admits that, after 15 years of designing the safeguards approach, the detection goals still cannot be met at the facility. In 2006, Shirley Johnson, the former head of the Rokkasho safeguards project in the IAEA's Department of Safeguards, acknowledged that even if the overall measurement uncertainty were between 0.7 and 0.8 percent at Rokkasho, the system could not come close to the detection goal of one SQ.[15] In a 2009 report for the International Panel on Fissile Materials (IPFM), Johnson reiterated the continuing problems in reducing measurement uncertainty, and called for complementary measures to address the concern:

> For a large facility like the Rokkasho Reprocessing Plant, which has an annual throughput of 800 tons of spent fuel containing about 1 percent plutonium (about 8,000-kg), a 1-percent uncertainty translates into an overall measurement uncertainty of 80 kilograms plutonium—10 significant quantities. For this reason, the IAEA requires added assurance by additional measures. Many of these could be carried out during short-notice random inspections.[16]

Unfortunately, such complementary measures have not yet been implemented. Nor have NRTA technologies solved the problem. Recent results from the performance of NDA solution monitoring systems at Rokkasho indicate that they also have high measurement uncertainty. For instance, it was reported that the Plutonium Inventory and Management System (PIMS), which is designed to perform assays on relatively pure plutonium and uranium mixtures, has a total measurement uncertainty of 6 percent (+/-).[17]

Although Japan sometimes blocks intrusive measures, claiming proprietary concerns, the IAEA has never accused the country of doing so out of an intention to divert fissile material. Indeed, it is despite Japan's apparent good-faith efforts to cooperate with the IAEA that its state-of-the-art safeguards have proved inadequate. As a result, the IAEA does not have high confidence that it could give timely warning of a potential diversion of enough fissile material for one or more nuclear weapons.

The shortcomings of safeguards are still greater in countries that withhold full cooperation from the IAEA and may have proliferation aspirations, such as Iran. As noted by the team that developed the safeguards approach for Rokkasho, "The most important factor leading to the success" of a safeguards system is "the open and full cooperation between all parties—the IAEA, the State, and the operator."[18] Thus, even potential future enhancements of safeguards would likely fall short if there were an uncooperative or adversarial relationship between these parties. This is a crucial consideration as the IAEA and the world consider the expansion of nuclear power and fuel-cycle facilities to states with uncertain commitments to nuclear nonproliferation.

Iran.

Since 2003, the IAEA and international community have become increasingly concerned that Iran may use its enrichment technologies to produce highly enriched uranium for a nuclear weapon. To date, Iran generally has enriched no higher than to 20 percent at its three declared enrichment facilities (except for one small batch that inexplicably was enriched to around 27 percent),[19] and mostly to only about 4 percent. Ostensibly, the 20-percent enrichment is for research-reactor fuel, and the 4-percent enrichment is for power-reactor fuel, although none of this uranium has yet actually been used as fuel.

Several experts have analyzed how quickly Iran could achieve a "breakout" by enriching sufficient highly enriched uranium (HEU) for a nuclear weapon. In October 2012, the Institute for Science and International Security assessed "that Iran would require at least 2-4 months to produce one SQ of WGU [weapons-grade uranium] at the Natanz Fuel Enrichment Plant," the largest of its three such facilities, if it started from its then existing stocks of low-enriched uranium. The report added that "the quickest estimates are 2 to 2.3 months."[20] Similarly, a Nonproliferation Policy Education Center (NPEC) report, published a month earlier, examined the breakout potential if Iran used all three of its enrichment facilities and concluded that "The total time required is 73 days, which is about 10 weeks or a little less than 2 1/2 months."[21]

At the moment, IAEA inspections should be able to detect such an attempted breakout at a declared Iranian facility because "currently, inspections occur on average about once every 2 weeks, and some of them are unannounced."[22] But if Iran expands the number of its centrifuges and attempts to implement next-generation centrifuges, the required time for a breakout would shrink substantially. For example, according to the NPEC report, if Iran expanded its number of centrifuges by 12 times—without any improvement in technology and starting only from its stock of 4 percent low enriched uranium (LEU) rather than its 20 percent enriched stock—"these enrichment facilities could produce enough HEU for a nuclear weapon in just 2 weeks."[23] At that point, the IAEA's current schedule of safeguards inspections could not guarantee timely warning against a diversion of sufficient HEU for a nuclear weapon, even if Iran used only its declared enrichment facilities. An additional danger is that Iran could pursue a breakout at a clandestine enrichment facility, which current IAEA safeguards might not detect. As the IAEA conceded in August 2012:

> While the Agency continues to verify the non-diversion of declared nuclear material at the nuclear facilities and LOFs [locations outside facilities] declared by Iran under its Safeguards Agreement, as Iran is not providing the necessary cooperation, including by not implementing its Additional Protocol, the Agency is unable to provide credible assurance about the ab-

> sence of undeclared nuclear material and activities in Iran, and therefore to conclude that all nuclear material in Iran is in peaceful activities.[24]

Suspected diversion from Iranian nuclear facilities is not merely hypothetical. The IAEA has reported accounting discrepancies at a separate Iranian nuclear facility, the Jabr Ibn Hayan Multipurpose Laboratories (JHL).[25] In 2011, the IAEA conducted a physical inventory verification at JHL "to verify, *inter alia*, nuclear material, in the form of natural uranium metal and process waste, related to conversion experiments carried out by Iran between 1995 and 2002."[26] This inspection revealed a discrepancy of 19.8-kg between the amounts of nuclear material declared by the operator and measured by the agency. Subsequently, in August 2012, after additional analysis and evaluation of clarifications provided by Iran, the agency reported that it had been able to reduce the discrepancy, and would continue to work with Iran to resolve the remainder.[27] As of the time this chapter was written in early-2013, however, the discrepancy had yet to be fully resolved, more than a year after it was originally discovered. This does not bode well, especially if Iran continues to expand its nuclear fuel-cycle facilities.

TWO RISKS: DIVERSION AND THEFT

Civilian nuclear fuel-cycle facilities present two risks of clandestine removal of fissile material: diversion by states or theft by sub-state insiders for criminal or terrorist purposes. In both cases, the adequacy of safeguards is critical to providing the international community with timely warning to prevent the removed material from being fabricated into one or more nuclear weapons. The fundamental goal of IAEA safeguards is to establish an accounting regime capable of reliably providing timely warning of the suspected clandestine removal of as little as one bomb's worth of fissile material, thereby helping to deter and prevent such an outcome. (This chapter does not cover the risks of overt attacks by sub-state actors on fuel-cycle facilities or shipments, or overt proliferation by states at formerly civilian facilities, which must be addressed by other national and international countermeasures.)

The potential for diversion and/or theft of bomb-usable nuclear material is present at three types of fuel-cycle facilities: (1) uranium enrichment, (2) reprocessing, and (3) MOX fuel fabrication. As explained later, these plants pose different vulnerabilities because of the different forms of fissile material that they routinely process.

Civilian enrichment facilities typically use centrifuges or other technologies to increase the percentage of the fissile U-235 isotope in uranium from its natural level of 0.7 percent to typically about 4 percent for use in the fuel elements of nuclear power plants. This output is known as "low enriched uranium," meaning less than 20 percent U-235, which is considered unsuitable for weapons. Civilian facilities typically do not produce "highly enriched uranium" (HEU)—meaning 20 percent or more U-235—which is considered necessary for weapons. Thus, the primary proliferation risks at civilian enrichment facilities are that the state could either (1) clandestinely produce and remove HEU, or (2) divert LEU to another facility not under safeguards for further enrichment.

Reprocessing facilities take the irradiated "spent" fuel that is removed from nuclear power plants and extract its plutonium (and uranium) for potential in-corporation into fresh MOX fuel to be irradiated in nuclear power plants. The separated plutonium poses a major security risk because it can be fabricated directly into a nuclear weapon. Typically, such facilities contain plutonium in the form of oxides and other chemical mixtures that can either be used directly to make less efficient weapons or converted to metal for improved efficiency.

MOX fuel fabrication facilities take the plutonium oxide from reprocessing plants and mix it with uranium oxide to fabricate mixed-oxide fuel for nuclear power plants. MOX plants pose several security risks. Most obviously, they contain large amounts of separated plutonium oxide that can be used to make nuclear weapons. But even after the plutonium is combined with uranium to make bulk mixed-oxide material, and subsequently fabricated into MOX fuel, significant risk continues because the plutonium oxide can be separated out via chemical processes that are relatively straightforward. (This is much easier than reprocessing because the fuel is fresh and thus not highly radioactive.)

SCOPE OF THE FACILITIES

The countries of main focus are those that have signed the Nuclear Nonproliferation Treaty (NPT) as non-nuclear weapon states, whose fuel-cycle facilities are subject to IAEA safeguards. But the chapter also discusses such facilities in nuclear-weapon states and in states that have not signed the NPT, as these plants may also offer some important lessons, especially if they are under stringent commercial safeguard regimes comparable to those of the IAEA.

Approximately 25 nuclear fuel-cycle facilities are operating in the world, with others proposed or temporarily closed, as detailed later. In 2012, there were 18 civilian enrichment plants operating, and three more were planned in 11 countries. Table 6-1 indicates their location, name, operational status, opening year, safeguards status, and capacity. Five commercial reprocessing facilities were operating, one was temporarily closed, and one was preparing to start up (see Table 6-2).

Country	Facility Name	Operational Status	Opening Year	Safeguards	Capacity [tSWU/yr]
Argentina	Pilcaniyeu	Operating	2010*	Yes	20 – 3,000
Brazil	Resende	Operating	2005	Yes	115-120
China	Shaanxi	Operating	1997	Yes	1,000
	Lanzhou II	Operating	2005	Offered	500
	Lanzhou (new)	Operating	2005	Yes	500
France	Georges Besse II	Operating	2011	Yes	7,500–11,000
Germany	Gronau	Operating	1985	Yes	2,200–4,500
Iran	Natanz	Operating	2004	Yes	120
	Qom	Operating	2012	Yes	5
Japan	Rokkasho	Operating	1992	Yes	1,500
Netherlands	Alemo	Operating	1973	Yes	5,000 – 6,000
Russia	Angarsk	Operating	1954	Offered	2,200–5,000
	Novouralsk	Operating	1945	No	13,300
	Zelenogorsk	Operating	2009	No	7,900
	Seversk	Operating	1950	No	3,800
United Kingdom	Capenhurst	Operating	1972	Yes	5,000
United States	Paducah, KY	Shutdown proposed	1954	Offered	11,300
	Piketon, Ohio	Planned	2013?	Offered	3,800
	Eunice, NM	Operating	2010	Offered	5,900
	Areva Eagle Rock, Idaho	Planned	Postponed	Offered	3,300–6,600
	Global Laser Enrichment, Wilm-ington, NC	Planned	2013	?	3,500–6,000

Sources: Nuclear Fuel Cycle Information System, Vienna, Austria: IAEA, available from *infcis.iaea.org/NFCIS/NFCISMain.asp?Order=1&RPage=1&Page=1&RightP=List;* and Global Fissile Materials Report 2011, Princeton, NJ: International Panel on Fissile Materials, p. 32.

Table 6-1. Civilian Enrichment Facilities.

Country	Facility Name	Operational Status	Opening	Safeguards	Capacity (tHM/yr)
China	Lanzhou Pilot Plant	Operating	2001	No	50–100
France	Areva La Hague UP2	Operating	1996	Yes	1,000
	Areva La Hague UP3	Operating	1990	Yes	1,000
Japan	Rokkasho	Starting Up	2007	Yes	800
	Tokai	Temporarily Shut Down	1977	Yes	200
United Kingdom	B205	To be closed after cleanup	1964	Yes	1,500
	THORP	Operating	1994	Yes	1,200

Sources: Nuclear Fuel Cycle Information System, Vienna, Austria: IAEA, available from *infcis.iaea.org/NFCIS/NFCISMain.asp?Order=1&RPage=1&Page=1&RightP=List;* and Global Fissile Materials Report 2011, Princeton, NJ: International Panel on Fissile Materials, p. 33.

Table 6-2. Civilian Reprocessing Plants.

As for MOX fabrication facilities, in the wake of the UK's 2011 announcement that its plant would close, only three commercial facilities—one each in France, Japan, and Russia—are currently in operation. Three more are planned to open during the next 4 years in Japan, Russia, and the United States (see Table 6-3). Japan Nuclear Fuel Ltd. had originally planned to open the Rokkasho-mura MOX plant in 2015, but the 2011 Fukushima nuclear disaster delayed construction on the facility by a year.[28] In Russia, the Mining & Chemical Combine plans to open a MOX facility at Zheleznogorsk in 2014. The U.S. MOX fuel facility at Savannah River will use plutonium from disassembled nuclear warheads and is scheduled to start operations in 2016 and begin producing commercial fuel in 2018.[29]

Country	Facility Name	Operational Status	Opening	Safeguards	Capacity (tHM/yr)
France	MELOX-Marcoule	Operating	1995	Yes (Euratom)	195
Japan	Tokai	Operating	2007	Yes	10
	Rokkasho	Planned	2016	Yes	130
Russia	Mayak - Paket	Operating	1980	No	5
	Zheleznogorsk	Planned	2014		60
United States	Savannah River	Planned	2018		100

Sources: *Nuclear Fuel Cycle Information System*, Vienna, Austria: IAEA, available from *infcis.iaea.org/NFCIS/NFCISMain.asp?Order=1&RPage=1&Page=1&RightP=List*; and "Mixed Oxide Fuel," London, UK: World Nuclear Association, available from *www.world-nuclear.org/info/inf29.html*.

Table 6-3. Civilian MOX Fuel Facilities.

TECHNICAL AND POLITICAL CHALLENGES

The nonproliferation community has been aware for decades of the technical and political challenges facing safeguards. In 1990, Dr. Marvin Miller of the Massachusetts Institute of Technology (MIT) published a seminal paper, "Are IAEA Safeguards on Bulk-Handling Facilities Effective?" highlighting these challenges. Despite some progress over the past 2 decades, many of the challenges that Dr. Miller highlighted in 1990 still persist.

IAEA safeguards for nuclear facilities were designed with the objective of detecting with timely warning the diversion of a significant quantity of fissile material. An SQ is the "approximate amount of nuclear material for which the possibility of manufacturing a nuclear explosive device cannot be excluded."[30] In other words, an SQ is the estimated minimum amount of uranium or plutonium (or other exotic fissile material) that a state or nonstate actor would need to build a nuclear weapon.

Depending on the type and form of fissile material, the IAEA guidelines adjust the amount that qualifies as an SQ and the deadline for timely warning. For unirradiated, direct-use nuclear material, an SQ is defined as 8-kg of plutonium, or 25-kg of U-235 in HEU, and timely warning is defined as 1 month after an abrupt diversion (or 1 year after the start of a gradual diversion). In 1975, the Standing Advisory Group on Safeguards Implementation (SAGSI) was established as a group of external experts appointed by the IAEA Director General to provide feedback on safeguards standards, among other functions.

Material accountancy is how the IAEA aims to detect the diversion of nuclear material at civilian fuel-cycle facilities. This is analogous to an audit. Operators of nuclear facilities prepare a material balance for a specific period of time showing that all nuclear material can be accounted for. To prepare this balance, the operators add material inputs—and subtract removals—from the quantity indicated at the start of the accounting period, yielding an amount that should match the ending physical inventory. The IAEA performs an independent assessment on at least some of the data provided by the facility operator to verify that there has not been any deliberate falsification of data.[31]

Discrepancies between the operator's final physical inventory and the amount that its records indicate should be present are labeled MUF. Such discrepancies can arise from problems such as accumulation of residual holdup in the process lines, accumulation of scrap and waste materials in other material forms that are hard to assay, inaccuracies in nuclear material estimation methods, operator incompetence, diversion, or theft. MUF is often caused by residual holdup, resulting from the adhesion of fissile-material powders on process equipment, including in cracks, corners, and pores. Because of the layout and design of fuel-cycle facilities, these MUFs can grow over time and may only be resolved by dismantlement and careful clean-out. Unless and until the source of the MUF can be identified, it is impossible to rule out the possibility of diversion or theft, which poses a dilemma. If inspectors declare a possible theft or diversion, it may well be a false alarm. But if they refrain from doing so for fear of a false alarm, it may be impossible to satisfy the IAEA's timely warning criteria.

False alarms thus pose a serious quandary for safeguards. The SAGSI guidelines recommend that safeguards be stringent enough to provide at least a 90 to 95 percent probability of detecting a diversion with a false alarm rate of less than 5 percent. Some critics have argued that this detection probability is too low, because it permits a 5 to 10 percent chance of a diversion going unnoticed. But merely raising the probability of detection, if all else remains equal, will also increase the false-alarm rate. Such increases in false alarms are a nuisance and impose costs by interrupting facility operations. Moreover, based on past experience, high false-alarm rates may spur operators to ignore alarms or even switch off the detection systems, thereby perversely reducing the probability of detection.

Unfortunately, real-world detection probabilities at fuel-cycle facilities are even lower than recommended by SAGSI. The IAEA has acknowledged that it cannot meet the goal of a 90 to 95 percent probability of detecting the diversion of an SQ. So, instead, the IAEA adopted a relaxed standard known as the "accountancy verification goal" (AVG), which was "based on a realistic assessment of what then-current measurement techniques could actually detect," according to a U.S. congressional report.[32] In other words, rather than designing safeguards to meet the desired detection standard, the IAEA instead has lowered that detection standard, so it could be satisfied by current safeguards.

The AVG is based on a measure called E, defined as the "minimum loss of nuclear material which can be expected to be detected by material accountancy," which varies depending on a facility's input, among other factors. The formula for E was derived from the joint requirements of a 95 percent confidence of detecting a diversion and a 5 percent false-alarm rate. For a large reprocessing facility, based on an input uncertainty of 1 percent (+/-) and an annual input of 800 metric tons of heavy metal (spent fuel), the value for E would be 246-kg of plutonium, or more than 30 SQs. In other words, there would be less than a 95 percent probability of detecting a diversion of 30 bombs' worth of plutonium. Any smaller diversion would have an even lower probability of detection. In particular, the probability of detecting the diversion of a single SQ—enough for a nuclear weapon—would be minimal.

Despite technological advances in monitoring and accounting systems since 1990, large MUFs have occurred repeatedly at facilities with IAEA-quality safeguards, as detailed earlier. These failures have arisen both in non-nuclear weapons states, subject to IAEA safeguards, and in nuclear weapons states subject to analogous domestic regulations.

PROPOSED IMPROVEMENTS

For at least 3 decades, nonproliferation experts have outlined theoretical proposals for improving safeguards. But practical obstacles, including proprietary concerns, have prevented their thorough implementation. In his 1990 paper, Miller focused on three areas:

1. **Reducing measurement uncertainty in the chemical process area**. Unfortunately, no progress is apparent in this realm. As of 2001, the IAEA's "expected measurement uncertainty" associated with closing a material balance at a reprocessing plant remains at 1 percent.[33] Miller reported the same value in 1990.

2. **Near-real-time accountancy on a weekly basis to improve the detection of protracted, low-level diversion**. In NRTA, inventories are taken and material balances closed on a much more frequent basis than the conventional annual physical inventory. For instance, Miller showed that the threshold for detection of an abrupt diversion of one SQ of plutonium at a fuel-cycle facility could be accomplished by use of NRTA with physical inventories conducted on a weekly basis. However, given that the time to take a physical inventory of a large facility is approximately 1 week—including preparation time, cleanout of process of equipment, measurement of the inventory, and reconciliation of the anomalies—such a high frequency of physical inventories is impractical.[34] Therefore, NRTA must resort to nondestructive assay measurements of in-process materials where possible, and its effectiveness will depend in large part on the uncertainties associated with these measurements. A major question is whether NDA techniques have improved over the past 22 years to the extent that the benefits of NRTA can be fully realized.

3. **Reducing measurement error of plutonium in the waste stream, such as in cladding hulls and sludges**. Over the past decade, Los Alamos National Laboratory and other labs have explored ways to improve the capabilities of NDA instruments for waste measurements. The development of neutron multiplicity counters and high-efficiency epithermal neutron counters showed some promise in improving the precision of measuring plutonium in waste drums. However, these instruments do not perform well when measuring low-assay, contaminated, and heterogonous plutonium materials—as is typical in waste streams.

A holistic approach to reducing measurement uncertainties is known as safeguards by design (SBD). Under SBD, future civilian nuclear fuel-cycle facilities would be designed, constructed, and operated in a manner to incorporate the most advanced technology and systems to enforce IAEA safeguards. Proponents of SBD assert that this approach can:

> ensure the timely, efficient, and cost effective integration of international safeguards and other nonproliferation barriers with national material control and accountability, physical protection, and safety objectives into the overall design process for a nuclear facility.[35]

But the future viability and success of SBD depends upon developing better monitoring and accountancy equipment, reducing the costs associated with these new designs and technologies, and alleviating proprietary concerns.

While such technical solutions could in theory enhance IAEA safeguards, proprietary and sovereignty concerns have hindered their implementation. States and nuclear firms have been reluctant to allow the

IAEA access to the design, construction, and operation of their fuel-cycle facilities because they fear loss of intellectual property. For example, in 2004, Brazil initially prevented IAEA officials from inspecting equipment at the Resende enrichment facility, in order to protect proprietary information. When the IAEA inspectors arrived at the plant, they discovered that large portions of it were behind walls and coverings.[36] Later in 2004, Brazil and the IAEA did reach an agreement to allow the inspectors to visit the site.[37] However, this incident demonstrates that even countries that have abandoned their pursuit of nuclear weapons and are responsible, active members of the international community (such as Brazil) are reluctant to provide the IAEA with unrestricted access to commercial fuel-cycle facilities due to proprietary concerns.

Other countries, such as Iran, may be hesitant to comply with the IAEA so that they can maintain their weapons option. Such countries may fear that the IAEA would provide detailed information about their facilities to their enemies. Top Iranian officials express this fear. For example, then-Iranian President Mahmoud Ahmadinejad labeled the head of the IAEA a puppet of the United States, and he accused the IAEA of making "illegal requests" during its inspection efforts.[38] In September 2012, the head of Iran's Atomic Energy Organization, Feyerdoon Abbasi-Davan, claimed that "terrorists and saboteurs might have intruded the agency and might be making decisions covertly."[39] Despite nominally placing all of its nuclear facilities under a safeguards agreement, Iran continues to deny the IAEA unfettered access to all of its nuclear-related facilities.

Given the limitations of safeguards, the IAEA increasingly has relied during the last 2 decades on complementary measures of containment and surveillance (C/S), especially seals and cameras. For example, reprocessing plants have begun to utilize seals on their tanks containing liquid plutonium nitrate, which is an interim form of the material during the plant's operation, in order to detect unauthorized withdrawals. Some reprocessing plants also have installed cameras to monitor the spent fuel pool and the transfer of spent fuel to the chop-leach cell to detect efforts to divert for clandestine reprocessing. Unfortunately, many parts of a reprocessing plant cannot be monitored with cameras or seals, because of the myriad pipes, valves, pumps, and tanks. Thus, although C/S measures are a useful complement to safeguards, they are no substitute for better accounting measures, such as NRTA.[40]

In 1997, due to concern about clandestine facilities, the IAEA introduced an additional protocol, which it aimed to negotiate with each state already subject to a comprehensive safeguards agreement. This would provide the IAEA "complementary access . . . to assure the absence of undeclared nuclear material and activities."[41] To induce states to sign the additional protocol and to save money, the IAEA also introduced the concept of integrated safeguards. Under this approach, the agency relaxes the inspection requirements at declared facilities, on grounds that its "state-level" approach can detect any nondeclared facilities where diverted material would need to be further processed for a nuclear weapon. The state-level approach depends on factors such as the state's own domestic accounting mechanisms and its willingness to accept remote monitoring and short-notice random inspections.[42] As the agency explains:

> when the IAEA has drawn a conclusion of the absence of undeclared nuclear material and activities in that State . . . [accountancy] measures may be applied at reduced levels at certain facilities, compared with the measures that would have been applied without this conclusion.[43]

SAGSI concluded in 2004 that such "Safeguards Criteria were basically sound,"[44] and in 2010, the IAEA reported that 47 states had implemented integrated safeguards.[45]

But serious questions have been raised about whether integrated safeguards are an adequate substitute for facility-level accounting. The approach depends on high confidence that the IAEA can detect all clandestine facilities in a country and that fissile material cannot be diverted to a second country for processing, both of which are questionable assumptions.[46] Some aspects of the state-level approach are laudable, including less predictable inspections and aiming to discover clandestine facilities,[47] but these should not come at the expense of watering down facility-level safeguards. Otherwise, integrated safeguards could wind up weakening, rather than strengthening, protections against misuse of fissile material.

Some nuclear security advocates, such as the IPFM, have proposed new ways to monitor fuel-cycle facilities in nuclear-weapons states—as would be required under a proposed Fissile Material Cut-Off Treaty (FMCT)—which might also be applicable at some facilities subject to IAEA safeguards.[48] To reduce costs of monitoring under an FMCT, an IPFM report in 2009 suggested that IAEA timeliness requirements could be relaxed in return for new verification and monitoring tools and methods, which it said would result in "only a relatively moderate increase in measurement uncertainties."[49] For example, at operating commercial facilities, the report recommended short-notice random inspections rather than continuous inspector presence.[50]

While IAEA safeguards are an international audit mechanism, analogous domestic measures are generally known as state systems of accounting and control (SSACs), which help monitor nuclear materials in a country and may provide the framework for the application of safeguards under an agreement between the state and the IAEA. These agreements include, but are not limited to, protocols for measurement systems to determine quantities of nuclear material and procedures governing the taking of a physical inventory. The IAEA does not have formal authority to address subnational threats, such as theft by workers at a facility ("insiders"). But improving SSAC to help the IAEA detect diversions by the state can also provide the operator an enhanced capability to detect diversions by sub-state insiders.[51] Unfortunately, additional aspects of domestic security that are important in countering internal threats, such as access authorization programs, remain out of the IAEA's formal domain, even under the provisions of the 2005 amendment to the Convention on Physical Protection of Nuclear Material which, in any case, has not yet entered into force. This distinction between state and nonstate actors is artificial when their interests are intertwined, so it may hinder efforts to build comprehensive systems to effectively ensure that civil nuclear facilities do not become covert sources of fissile material for states or subnational groups.

Domestic authorities also are responsible for "physical protection," which seeks to detect and prevent loss of nuclear material in real time, in contrast to accountancy that can only detect it after the fact. Many of the technological aspects of physical protection are known as material control and accounting (MC&A), which comprises aspects of safeguards, in addition to containment and surveillance. At fuel-cycle facilities, MC&A includes but is not limited to locks, fences, walls, gates, and badging systems. It also may incorporate interior and exterior sensors such as video cameras and motion detectors to prevent outsiders from breaking in or insiders from gaining access to sensitive areas and materials, and to improve response time to alarms. Such systems also may monitor pedestrian and vehicle exits to detect attempts to remove materials.[52] Beyond MC&A—which comprises these technological approaches to detection, deterrence, and prevention of nuclear theft—physical protection programs also include additional response and deterrence elements, including armed forces.

CONCLUSION

Theoretical solutions to improve IAEA safeguards have been discussed for decades. However, proprietary, economic, and sovereignty concerns have limited the extent to which countries and private companies have implemented these theoretical solutions. Even in states that cooperate with the IAEA and apply sophisticated accounting mechanisms, such as Japan, safeguards at fuel-cycle facilities currently cannot come close to achieving their explicit goal of providing timely warning of a suspected diversion of one bomb's worth of fissile material. The prospects are even worse in states that resist cooperation and may wish to keep open their weapons option, such as Iran, and at facilities that employ first-generation safeguards.

If the prospect of an undetected diversion or theft of fissile material is unacceptable to the international community, then it is imprudent to permit the construction of additional nuclear fuel-cycle facilities, or expansion of existing ones, especially in states of proliferation concern, unless and until safeguards can be substantially upgraded to meet the international community's explicit detection goals. Considerable resources should be devoted to research and development of such improvements. But if past experience is any indicator, significant progress is unlikely to occur anytime soon. That stubborn reality should inform nuclear policy decisions. Most importantly, it suggests that the international community should postpone consideration of expanding the recycling of spent nuclear fuel, because that would require additional reprocessing and MOX fuel fabrication facilities that cannot now be safeguarded adequately against diversion or theft for nuclear weapons.

ENDNOTES - CHAPTER 6

1. This chapter draws upon a previously published chapter. See Edwin S. Lyman, "Can Nuclear Fuel Production in Iran and Elsewhere Be Safeguarded Against Diversion?" Henry Sokolski, ed., *Falling Behind: International Scrutiny of the Peaceful Atom*, Carlisle, PA: Strategic Studies Institute, U.S. Army War College, 2008, pp. 101-120.

2. BNFL, "Media Response: Publication of Materials Unaccounted For (MUF)," press release, February 17, 2005.

3. BNFL, Board of Inquiry Report, "Fractured Pipe With Loss of Primary Containment in the THORP Feed Clarification Cell," May 26, 2005, p. 5.

4. *Ibid.*, p. 15.

5. Barry Jones *et al*., BNFL, and Claude Norman *et al*., European Commission, Euratom Safeguards Office, "NRTMA: Common Purpose, Complementary Approaches," IAEA-SM-367/8/03, IAEA Safeguards Symposium, October-November 2001, IAEA, Vienna, Austria.

6. *Ibid*., p. 5.

7. European Commission, "Report from the Commission to the European Parliament and Council: Operation of Euratom Safeguards in 2002," p. 9.

8. Ann MacLachlan, "With Eurofab imminent, MUF issue said cleared up for Cadarache plant," *Nuclear Fuels*, Vol. 29, No. 20, September 27, 2004, p. 12.

9. Ann MacLachlan, "CEA, Areva Criticized for Handling of Plutonium at Closed ATPu Plant," *Nuclear Fuels*, Vol. 34, No. 21, 2009.

10. Edwin S. Lyman, "Japan's Plutonium Fuel Production Facility: A Case Study of the Challenges of Nuclear Material Accountancy," 39th Annual Meeting of the Institute of Nuclear Materials Management (INMM), Naples, FL, July 1998.

11. Mark Hibbs, "PFPF Holdup Pu Inventory Under 10 kg; R&D Work to Focus on Monju Fuel," *Nuclear Fuel*, November 4, 1996, p. 15.

12. *IAEA Safeguards Glossary,* 2001 Ed., Vienna, Austria: IAEA, Table III, p. 53, available from *www-pub.iaea.org/MTCD/publications/PDF/nvs-3-cd/PDF/NVS3_prn.pdf.*

13. *IAEA 1998 Annual Report*, p. 65.

14. *IAEA 2000 Annual Report*, p. 102, available from *www.iaea.org/Publications/Reports/Anrep2000/safeguards.pdf*.

15. Shirley Johnson, IAEA, personal communication, July 27, 2006.

16 . Shirley Johnson *et al*., "Meeting the Safeguards Challenges of a Commercial Reprocessing Plant," 7th International Conference on Facility Operator-Safeguards Interface," Charleston, SC, February 29-March 4, 2004, p. 10.

17. Y. Noguchi, "Validation and Performance Test of Plutonium Inventory Measurement System (PIMS) at Rokkasho Reprocessing Plant (RRP)," Institute of Nuclear Materials Management 48th Annual Meeting, Tucson, AZ, July 8-12, 2007.

18. Johnson *et al*., "Meeting the Safeguards Challenges of a Commercial Reprocessing Plant."

19. "Implementation of the NPT Safeguards Agreement and relevant provisions of Security Council resolutions in the Islamic Republic of Iran," GOV/2012/23, Vienna, Austria: IAEA, May 25, 2012, p. 6.

20. William C. Witt, Christina Walrond, David Albright, and Houston Wood, "Iran's Evolving Breakout Potential," Washington, DC: Institute for Science and International Security (ISIS), October 8, 2012, available from *isis-online.org/uploads/isis-reports/documents/Irans_Evolving_Breakout_Potential.pdf*.

21. Greg S. Jones, "'Not a Game-Changer' But Is the West Playing a Game with Iran That It Has Already Lost?" Washington, DC: Nonproliferation Policy Education Center (NPEC), September 10, 2012, available from *www.npolicy.org/article.php?aid=1193&rid=4*.

22. David Albright, Christina Walrond, William Witt, and Houston Wood, "Comments on Wall Street Journal Editorial and Our Breakout Estimates," Washington, DC: ISIS, October 30, 2012, available from *isis-online.org/isis-reports/detail/comments-on-wall-street-journal-editorial-and-our-breakout-estimates/*.

23. Jones, "'Not a Game-Changer'."

24. "Implementation of the NPT Safeguards Agreement and relevant provisions of Security Council resolutions in the Islamic Republic of Iran," GOV/2012/37, Vienna, Austria: IAEA, August 30, 2012, p. 11.

25. "Nuclear Iran: Jabr Ibn Hayan Multipurpose Laboratories," Washington, DC: ISIS, available from *www.isisnucleariran.org/sites/detail/tehran/*.

26. "Implementation of the NPT Safeguards Agreement and relevant provisions of Security Council resolutions in the Islamic Republic of Iran," GOV 2012/9, Vienna, Austria: IAEA, February 24, 2012, available from *www.iaea.org/Publications/Documents/Board/2012/gov2012-9.pdf*.

27. "Implementation of the NPT Safeguards Agreement," August 30, 2012.

28. "MOX Plant Construction Shown," *The Japan Times*, November 2, 2012, available from *www.japantimes.co.jp/text/nn20121102b2.html*.

29. Rob Pavey, "MOX Facility at SRS Gets Powdered Plutonium Feedstock," *The Augusta Chronicle*, November 16, 2012, available from *chronicle.augusta.com/news/business/2012-11-16/mox-facility-srs-gets-powdered-plutonium-feedstock.*

30. *IAEA Safeguards Glossary*, p. 23.

31. *Ibid.*, p. 277.

32. U.S. Congress, Office of Technology Assessment, Nuclear Safeguards and the International Atomic Energy Agency, OT ISS-615, Washington, DC: U.S. Government Printing Office, June 1995, p. 73.

33. *IAEA Safeguards Glossary*, p. 53.

34. Thomas G. Clark *et al.*, Westinghouse Savannah River Company, "Continuous Material Balance Reconciliation for a Modern Plutonium Processing Facility," 45th Annual Meeting of the Institute of Nuclear Materials Management (INMM), July 18-22, 2004, Orlando, FL.

35. T. Bjornard *et al.*, "Improving the Safeguardability of Nuclear Facilities," presented at Institute of Nuclear Materials Management 50th Annual Meeting, July 2009, available from *www.inl.gov/technicalpublications/Documents/4310590.pdf*.

36. “Sources: Brazil blocks nuclear inspectors,” *CNN*, April 4, 2004, available from *www.cnn.com/2004/WORLD/americas/04/04/brazil.nuclear/index.html*.

37. “Diplomats: IAEA, Brazil Reach Agreement,” *USA Today*, October 6, 2004, available from *usatoday30.usatoday.com/news/world/2004-10-06-brazil-nukes_x.htm.*

38. “Iran Does Not Need Nuclear Weapons, Says Ahmadinejad,” *BBC*, November 8, 2011, available from *www.bbc.co.uk/news/world-middle-east-15637539*. “Ahmadinejad: Iran ‘Could Have Behaved Better’, IAEA Has ‘Double Standards’,” *Christian Science Monitor*, September 25, 2012, available from *www.csmonitor.com/World/Middle-East/2012/0925/Ahmadinejad-Iran-could-have-behaved-better-IAEA-has-double-standards*.

39. “Iran Warns of IAEA ‘Terrorist Infiltration’,” *BBC*, September 17, 2012, available from *www.bbc.co.uk/news/world-middle-east-19627623*.

40. Marvin Miller, “Are IAEA Safeguards on Plutonium Bulk-Handling Facilities Effective,” Paul L. Leventhal *et al*., eds., *Nuclear Power and the Spread of Nuclear Weapons*, Washington, DC: Brassey’s, 2002, pp. 283-284.

41. Mark Hibbs, “The Unspectacular Future of the IAEA Additional Protocol,” Washington, DC: Carnegie Endowment, April 26, 2012, available from *carnegieendowment.org/2012/04/26/unspectacular-future-of-iaea-additional-protocol*.

42. *IAEA Safeguards: Staying Ahead of the Game*, Vienna, Austria: IAEA, July 2007, available from *www.iaea.org/Publications/Booklets/Safeguards3/safeguards0707.pdf*.

43. *IAEA Safeguards Glossary*, p. 28.

44. “IAEA, Safeguards Statement for 2004,” para. 52, p. 11.

45. “IAEA, Safeguards Statement for 2010,” available from *www.iaea.org/safeguards/documents/es2010.pdf.*

46. Ed Lyman, "Role of nuclear material accounting and control in the NPT," IEER Conference, Nuclear Dangers and the State of Security Treaties, United Nations, New York, April 9, 2002.

47. Herman Nackaerts, "The Future of Safeguards: Adapting to Change," January 17, 2012, available from *www.iaea.org/OurWork/SV/Safeguards/DDG-Corner/dg-statements-repository/TheFutureOfSafeguards.html*.

48. Shirley Johnson, *The Safeguards at Reprocessing Plants under a Fissile Material (Cutoff) Treaty,* Princeton, NJ: International Panel on Fissile Materials, February 2009, available from *fissilematerials.org/library/rr06.pdf*.

49. *Ibid*., p. 8.

50. *Ibid*., p. 10.

51. Miller, "Are IAEA Safeguards on Plutonium Bulk-Handling Facilities Effective?" p. 273.

52. Office of International Affairs, National Research Council, *Protecting Nuclear Weapons Material in Russia*, Washington, DC: National Academy Press, 1999, p. 53.