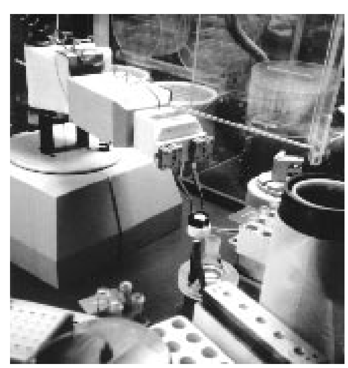
Appendix A: Safeguarding Reprocessing Facilities

A

This appendix focuses on the issue of safeguards at reprocessing plants, a type of bulk-handling facility of particular interest because it produces large quantities of plutonium that can be used to make nuclear weapons. Although there is only one currently operating reprocessing facility under INFCIRC/153-type safeguards (Japan's Tokai plant), there are several large plants in operation or to be built in the future.[1] The other large plant that will be under INFCIRC/153 safeguards is the Rokkasho-mura plant in Japan, which is expected to begin full operation in about 2005 (see table A-1).[2]

The ability of safeguards to assure the nondiversion of "significant quantities" of plutonium from large reprocessing plants has been the subject of considerable attention and controversy for many years. The major technology holders have been studying these issues under the auspices of the LASCAR (Large Scale Reprocessing) forum since the late 1980s and have completed a major study.[3] This appendix will describe the basic safeguards ap-



[1]Those in operation, however, are in nuclear weapon states—France, the United Kingdom, and Russia—that are not required to place their nuclear facilities under IAEA safeguards. Parts of the several reprocessing plants in France and the United Kingdom are safeguarded under the voluntary offer these states have made to place certain facilities under IAEA safeguards. However, these safeguards do not extend to the entire plant.

[2]N. Usui and A. MacLachlan, "Japan AEC Looking at Delay in Startup of Reprocessing Plants," *Nuclear Fuel*, Feb. 14, 1994, pp. 10-11.

[3]The only publicly available document from LASCAR is the booklet *Report of the LASCAR Forum: Large Scale Reprocessing Plant Safeguards,* STI/PUB/922 (Vienna, Austria: IAEA, July 1992).

TABLE A-1: Civil Reprocessing Facilities

Location	Plant name	Capacity[a]	Operational status	Safeguards status
NPT nuclear-weapon states (NWS):				
France (Cap de la Hague)	Cogema UP2[b], UP3	800 t HM (LWR fuel)/yr each; 1,600 t HM/yr total	In operation; UP2 since 196& UP3 since 1990	Limited IAEA safeguards through nuclear-weapon-state voluntary offer LASCAR involvement with UP3
France (Marcoule)	Cogema UP1	400 t HM (metal fuel)/yr[d]	1958- 2000?	(EURATOM only)[c]
France (Marcoule)	CEA APM	6 t HM (FBR fuel)/yr	1988- present	(EURATOM only)
Russia (Chelyabinsk-40)	Mayak	600 t HM (LWR fuel)/yr	1978- present	No
United Kingdom (Sellafield)	Windscale B205	1,500 t HM (magnox)/yr	1964-201 O?	(EURATOM only)
United Kingdom (Sellafield)	Thermal Oxide Reprocessing Plant (THORP)	1200 t HM (LWR fuel)/yr	In commissioning	EURATOM; limited IAEA safeguards under United Kingdom voluntary offer to the IAEA LASCAR involvement
United Kingdom (Thurso)	Fast Reactor Fuel Reprocessing Plant; (Dounreay)	7 t HM (FBR fuel)/yr[d]	In operation; (1958 - 1995?)	Limited IAEA safeguards for period (1980-1982) through United Kingdom voluntary offer; training and R&D
USA (West Valley)	Nuclear Fuel Services (NFS)	300 t HM (LWR fuel) / yr	1966-1972 (retired)	Training and R&D
NPT non-nuclear-weapon states (NNWS) with potential for large reprocessing capability:				
Germany (Karlsruhe)	Wiederauf-Arbeitungs Anlage Karlsruhe (WAK)	35 t HM (LWR fuel)/yr	1971-1991	IAEA NPT safeguards; EURATOM
Germany (Wackersdorf)	Wiederauf-Arbeitungs Anlage Wackersdorf (WAW)	500 t HM (LWR fuel)/yr	Canceled	Planning, R&D; LASCAR involvement
Japan (Tokai-mura)	Tokai Reprocessing Plant	90 t HM (LWR/ATR fuel)/yr	In operation (startup 1981)	IAEA NPT safeguards
Japan (Rokkasho-mura)	Rokkasho Reprocessing Plant	800 t HM (LWR fuel)/yr	Under construction (startup 2005?)	IAEA NPT safeguards; LASCAR involvement

TABLE A-1 (Cont'd.): Civil Reprocessing Facilities

Location	Plant name	Capacity	Operational status	Safeguards status
Japan (Tokai-mura)	Chemical Process Facility	Fast reactor R&D reprocessing plant[d]	1982-1987	IAEA NPT safeguards
Japan (Tokai-mura)	Recycle Engineering Technology Facility (RETF)	24 t HM (LMR fuel)/yr	Under license review	IAEA NPT safeguards
NPT non-nuclear-weapon states with small to medium scale reprocessing capability:				
Belgium (Mel)	Eurochemic	30-60 t HM (LWR and MTR fuel)/yr	1966-1974	IAEA safeguards applied after plant shut down; EURATOM
Italy (Saluggia)	EUREX	20 t HM (LWR fuel)/yr	Shut down	IAEA NPT safeguards; EURATOM
Italy (Rotondella)	ITREC	4 t HM (Th fuel)/yr	Shut down	IAEA NPT safeguards (EURATOM)
Italy (Ispra)	Petra	Experimental; TRU waste R&D	Awaiting commissioning	IAEA NPT safeguards (EURATOM)
NPT (or otherwise safeguarded) states of past or current proliferation concern:				
Argentina (near Buenos Aires)	Ezeiza	[5 t HM/yr]	Suspended 1990	Partly
Brazil (Resende)		[3 t HM/yr]	Suspended 1980s	Yes
DPRK (Yongbyon)	Radiochemical Laboratory	Confidential [pilot scale?]	Confidential [1992?]	Nominally IAEA NPT safeguards, but now in violation
Iraq (Tuwaitha)	No name given	Confidential [lab scale]	1989-1991 (destroyed)	Violation
South Africa (Pelindaba)		[Pilot scale]	[1987 - ?]	IAEA NPT safeguards
Non-NPT states:				
India (Tarapur)	PREFRE	100 t HM (Candu fuel)/yr	In operation (commissioned 1982)	IAEA safeguards only when safeguarded fuel is reprocessed
India (Trombay)	B. A.R.C.	30 t HM/yr	1966 - 1974; [and 1983- present?]	No
India (Kalpakkam)		[100-200 t HM/yr?]	Planned startup 1993/1994?	No
Israel	Dimona	[50 -100 t HM/yr]?	1966? - present?	No

(continued)

TABLE A-1 (Cont'd.): Civil Reprocessing Facilities

Location	Plant name	Capacity	Operational status	Safeguards status
Pakistan (Chasma)		Planned 100 t HM/yr	Construction may have ended 1978	No (but IAEA safeguards had been planned)
Pakistan (Rawalpindi)	New Labs	[5 t/ HM yr?]	Believed not to be operating	No

[a] Capacity in tons per day is generally about 1/200 times the capacity given in tons per year. Items in [brackets] or with question marks represent estimates or substantial uncertainty, respectively.

[b] UP2 operated at 400 t HM/yr capacity until 1990; its upgrade, UP2-800," began operating in 1992. The latter, along with UP3, will be involved with limited IAEA safeguards.

[c] All *civilian* nuclear material in European Community member states (even in France and Britain) is safeguarded by EURATOM under EC Regulation 3227/76. However, because they are nuclear weapon states, France and Britain are not obligated to place their facilities under IAEA safeguards.

[d] Because FBR fuel contains relatively large fractions of plutonium, a given reprocessing capacity (in terms of spent FBR fuel) translates to a plutonium throughput up to 15 times higher than would result from reprocessing the same amount of typical light-water reactor spent fuel.

KEY: CEA = Commissariat a' l'E'nergie Atomique; Cogema = Compagnie Ge'ne'rale des Matie'res Nucle'aires; FBR = fast breeder reactor (liquid metal reactor); HM = heavy metal; LASCAR = IAEA forum on large-scale reprocessing; LWR = light-water reactor; magnox = type of reactor; MTR = materials test reactor; TRU = transuranic

SOURCE: Adapted from Thomas Shea et al., "Safeguarding Reprocessing Plants: Principles, Past Experience, Current Practice and Future Trends," *Journal of Nuclear Materials Management,* July 1993, p. 20; David Albright, Frans Berkhout, and William Walker, *World Inventory of Plutonium and High/y Enriched Uranium, 7992* (Oxford, United Kingdom: Oxford University Press/SIPRl, 1993), p. 90; Leonard S. Spector and Jacqueline R. Smith, *NuclearAmbitiorts: The Spread of Abe/ear Weapons, 7989-7990*(Boulder, CO: Westview Press, 1990); and James E. Lovett, "Nuclear Materials Safeguards for Reprocessing," International Atomic Energy Agency Report STR-151/152, December 1987, pp. 25-36.

preach and attempt to evaluate the current understanding of the safeguardability of reprocessing plants.[4]

In general, nuclear safeguards are concerned with monitoring items or amounts of material held in material balance areas (MBAs). MBAs are separate parts of a facility within whose boundaries reliable inventories of nuclear materials can be established, and material flows in or out can be monitored. Flows are measured at predetermined locations known as "key measurement points," and samples may be taken from various tanks, containers, and storage areas. Bulk-handling facilities may be divided into several MBAs: sometimes the first will encompass a receipt and storage area (for spent fuel, plutonium, or uranium) and, for reprocessing plants, the head-end fuel shearing and dissolution area, where spent fuel rods are chopped up and dissolved; the second comprises the process area; and the third, a product storage area (see figure A-1).[5] Until recently, the thinking in the safeguards community was that increasing the number of MBA's would increase effectiveness. However, it is now realized that multiple MBA's require extensive reporting of inventory changes and separate material balance reports, increasing the work of operators, state authorities, and IAEA staff. The current approach is to move toward increasing the amount of data in the process available to the IAEA, enabling localization down to small process cells, through process monitoring and near-real-time accountancy (NRTA), but without the burden of additional MBAs.

[4] Additional information on safeguards of reprocessing plants is presented in Burton Judson, "Needs and Obstacles in International Safeguards of Large Nuclear Fuel Reprocessing Plants," contractor report to OTA, December 1993, NTIS No. PB95-199170.

[5] Frans Berkhout and William Walker, "Safeguards at Nuclear Bulk Handling Facilities," in J.B. Poole and R. Guthrie (eds.), *Verification Report 1992* (London, U. K.: VERTIC, 1992), pp. 199-209.

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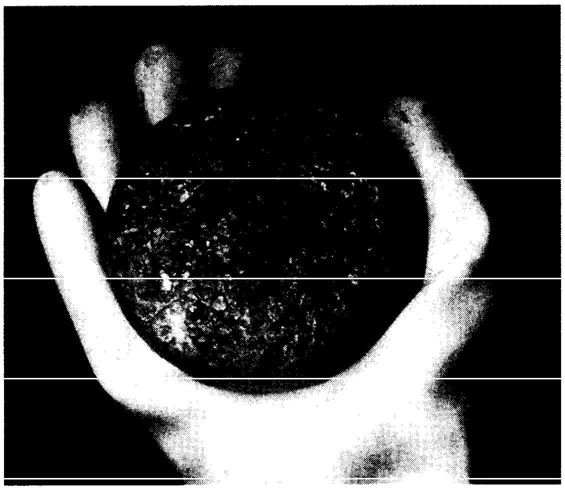


Plutonium metal from the U.S. weapon program. In civil reactors, plutonium is practically always used in oxide, rather than metallic, form.

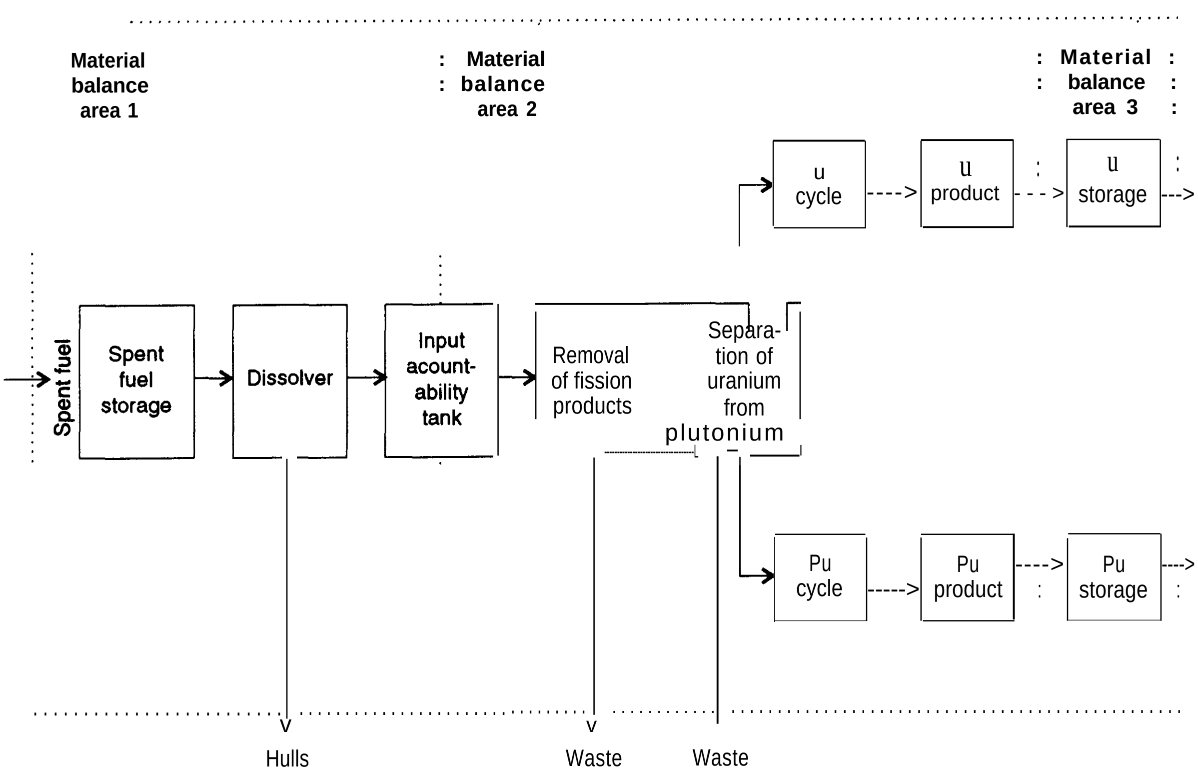
As with other types of facilities, the basic safeguards approach for reprocessing plants is material accountancy, supplemented by containment and surveillance (C/S) techniques. C/S is used primarily to keep track of items that have already been measured in the input and product storage areas, and particularly for items in transit from the input storage area to the head end of the process area. C/S is also intended to provide assurance that plant operations conform to declarations given to the IAEA—that there are no undeclared reprocessing campaigns or attempts to bypass key measurement points available to the IAEA. At the head end, fuel assemblies are chopped into small pieces and dissolved in nitric acid, transforming them from discrete into bulk form. At this point, verification requirements become less amenable to C/S measures.. The C/S equipment currently in routine use consists almost entirely of seals and camera or video surveillance.

The "process area" consists of everything between the head end and the point at which the separate plutonium (and uranium) product streams are converted into solid form and transferred once again into discrete containers and stored.[61] **Because the plutonium in the process area of reprocessing plants is dissolved in solution—and because large plants process so much of it over the course of a year—accurate material-accountancy measurements to assure that none has been diverted pose significant challenges.** Further, much of the process involves highly radioactive streams, which change chemical composition and concentration many times and must be handled remotely behind thick radiation shielding. While a multitude of process variables are controlled and monitored by computers, access to the actual materials for measurement purposes is quite limited.

To address these challenges, the IAEA and operators of reprocessing plants have taken several approaches. First, they have worked to improve the accuracy associated with each of the various measurement techniques used in applying material accountancy. Second, they have examined the use of near-real-time accountancy techniques, in which material inventories within various stages of processing, as well as flows in and out of these stages, are monitored daily or weekly. (See box A-l.) NRTA methods improve the *timeliness* of diversion detection over conventional materials accountancy methods, since NRTA inventories are monitored more frequently. NRTA can also improve detection *sensitivity* by applying statistical tests to the much larger data sets that are generated. Third, the IAEA and plant operators have sought to acquire a much more thorough understanding of safeguards-relevant design information for such plants by early reporting of design information, and by verification of plant designs during construction. Finally, and most important, there is increasing reliance on detailed process monitoring by the IAEA to obtain real-time data on inter-vessel transfers. This monitoring will

[61] In some plants, however, including Rokkasho the reprocessing plant's output, in the form of plutonium nitrate solution, is piped directly to a separate conversion plant for metal-oxide fuel production, rather than converted to plutonium oxide powder and stored.

FIGURE A-1: Material Balance Areas for a Plutonium Reprocessing Plant



SOURCE: Modified from figure in S.J. Johnson and A. B. MN. Islam, "The Current IAEA Approach to Implementation of Safeguards in Reprocessing Plants," *Proceedings of the Fourth International Conference on Facility Operations-Safeguards Interface,* Albuquerque, NM, Sept. 29-Oct, 4, 1991 (La Grange Park, IL: American Nuclear Society, 1992).

help assure that the plant is being operated according to the operator's declarations and also provides input data for NRTA.

Understanding design information complements the primary safeguards approach of material accountancy in much the same way as do C/S techniques. An anomalous inventory measurement or large amount of material unaccounted for (MUF) could indicate the possibility of diversion, but it would rarely be definitive. If material is to be diverted from the plant, it must be removed by some physical means in a plausible way. Verification of plant design information plays an important role in giving added assurance against the existence of unmonitored diversion paths. It is also necessary to ensure, for example, that what is purported to be drawn from a particular tank was indeed drawn from that tank and no other. For this purpose, data from process monitoring is vital.

At each point in a reprocessing plant, diversion of useful material would require overcoming significant obstacles. At vulnerable points where items are routinely moved around (e.g., at the head end and product areas), cameras and other monitoring techniques watch for the possibility of diversion. This is especially important before the spent fuel rods are chopped up, and after plutonium output streams are converted into plutonium oxide powder, sealed into cans, and placed in storage using automated material-handling equipment. Additional measures are taken to ensure that areas such as the plutonium stores are heavily

BOX A-1: New Approaches to Material Accountancy for Reprocessing Plants[1]

Through the mid-1980s, one of the criteria for successful application of reprocessing-plant safeguards involved meeting the so-called Accountancy Verification Goal (AVG). The AVG was set at either 8 kg plutonium or 3,3 percent of annual plutonium throughput, whichever was larger.[2] For small plants processing up to 30 t light-water reactor spent fuel per year, 3,3 percent of throughput does not exceed 8 kg and the difference between the AVG and the 8 kg significant quantity (SQ) is irrelevant. (Of all reprocessing plants that had been fully safeguarded up to that point, only the Tokai facility, at 90 t/yr, had exceeded this level.[3] In addition, the safeguards approach required the IAEA to apply various tests of statistical significance to material unaccounted-for (MUF) values and to operator/inspector differences—the differences between values of various quantities (material inventories, etc.) as reported by the plant operator and as independently verified by the IAEA.[4] Discrepancies that were deemed significant by these tests required investigation. **Nevertheless, the criteria for statistical significance were often difficult to satisfy because the needed measurement-error-variance data either were incomplete or were not of sufficient quality to lend confidence to the conclusions.** Without valid measurement uncertainty data, the whole question of detection probability becomes meaningless. Therefore, the practical result of not having good uncertainty data was that inspectors rarely had firm grounds on which to challenge operator declarations.[5] More recently, the IAEA has been estimating operator measurement errors by comparing IAEA measurements with operator measurements of identical samples over time.

In large commercial reprocessing facilities, the uncertainty associated with the verification of material-unaccounted-for, or σ (MUF), can easily exceed 8 kg (1 SQ) at a year-end physical inventory. Thus, 3.3 σ (the size of a diversion that would be detected with 95 percent confidence at a 5 percent false positive rate; see box 3-2 of the main text) can be much larger than 1 SQ. Therefore, even facilities meeting their AVG might nevertheless have lost well over one SQ to diversion in the course of a year without being detected by material balance evaluations, Recognizing this, and in an attempt to achieve timely detection, facility operators and safeguards agencies have sought chiefly to improve upon traditional materials accountancy. At the same time, the IAEA has phased out use of the AVG, and the revised Safeguards Criteria introduced in 1991 make no reference to the concept,

Even though the AVG is no longer in use, *conventional* material accountancy methods alone appear unable to verify the absence of diversion or loss of material from large reprocessing plants to within annual uncertainty levels of 1 SQ of plutonium. At least four techniques to improve upon conventional material accountancy have been described, The running book inventory (RBI) and cumulative flux method techniques are similar and are only appropriate to plants operating in steady

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[1]This box draws significantly from Frans Berkhout and William Walker, "Safeguards at Nuclear Bulk-Handling Facilities, " in *Verification Report* 1992 (London, UK: VERTIC, 1992), pp. 199-209.

[2]J.E. Lovett, "Nuclear Materials Safeguards for Reprocessing," International Atomic Energy Agency Report STR-151/152, December 1987, p. 138. This threshold is based on an overall measurement uncertainty (one standard deviation) of 1 percent of throughput times the factor of 3.3 by which a diversion must exceed measurement uncertainty in order to be detected with a 95 percent detection likelihood at a 5 percent false alarm rate. See box 3-2 in the main text,

[3]India's PREFRE facility, at 100 t/yr, also exceeded this level, but it was only safeguarded during three campaigns between 1982 and 1985, when safeguarded fuel was present. Voluntary offers from the United Kingdom and France for safeguarding certain aspects of their own large reprocessing facilities came later, and in any case were usually limited in scope, such as being applied only to spent fuel storage and product areas. As nuclear weapon states, the United Kingdom and France are not required to put any of their nuclear facilities under safeguards.

[4]Lovett, op. cit., footnote 2, p. 138.

[5]Ibid., pp. 140, 173.

BOX A-1 (Cont'd.): New Approaches to Material Accountancy for Reprocessing Plants

state, and for which the in-process inventory is small. Neither is acceptable to the IAEA for large plants. (These approaches have little value during periods of startup, shutdown, or other process upsets.) Book inventories for a given plant are calculated simply by subtracting the plutonium outputs from inputs (each measured), with no attempt at measuring any portion of the actual in-process inventory. Diversion is assumed not to have taken place if these inventories fall within predetermined limits (smaller than an SQ). An approach using RBI was being applied at the UP2(400) plant at La Hague. At that facility, the amount of material being processed at any one time was normally quite small, passing through the plant in two days to a week.

In contrast, adjusted running book inventory (ARBI) and near-real-time accountancy (NRTA) involve in addition the direct measurement of *in-process* inventories, so that data are available with which to apply various statistical tests to MUF figures (and their explanations in terms of measurement uncertainties). ARBI is distinguished from NRTA in its reference to past data on process variables in an MBA. ARBI and NRTA are particularly necessary when wide variations in process inventories are expected, as in the process areas at THORP in the United Kingdom and Rokkasho-mura in Japan, both of which are designed with large buffer tanks that allow such wide fluctuations in process inventories. At THORP, for example, process inventories may approach 0.6 tonnes of plutonium. Since at any time, more than 80 percent of this inventory may reside in the buffer and accountability tanks, it is amenable to direct measurement.

The basic principle of NRTA is that the in-process inventory of plutonium is frequently monitored (perhaps daily or weekly) using a combination of direct measurements from in-process instruments, off-line analyses, and indirect measurements using computer simulations of the chemical process areas.[6] Most tanks and many process vessels are amenable to measurement or estimation of actual inventory or of minimum operating inventories. One obvious advantage is that the throughput over a short interval is significantly smaller than that over an entire year, so that the effects of some of the overall measurement uncertainties are proportionally reduced. Another is that many more measurements are taken, permitting the use of various statistical tests on the additional data and effectively increasing the detection timeliness over that of monthly interim inventories.

The in-process inventory measurement is evaluated by looking for unexplained *trends* in the derived MUF values. However, to calibrate the NRTA system, a baseline must first be established by obtaining a sequence of MUF values over a substantial length of time under conditions where it can be assured that no diversion is taking place. Under such conditions, all deviations observed in MUF values must be due to measurement error and to unreported plant losses such as hold-up (the retention of small amounts of plutonium in pipes and at the bottom of tanks). During subsequent operation of the plant, MUF values can be compared with this baseline, which represents the systematic errors in the measurement system, Use of this baseline data effectively reduces the magnitude of σ (MUF), improving the sensitivity of detection. The development of a baseline is begun as part of the design information verification activities during cold and hot plant commissioning.

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[6]For instance, direct measurement is not feasible in certain types of process equipment, such as Contractors and evaporators, which might account for 10 percent of the total in-process inventory.

BOX A-1 (Cont'd.): New Approaches to Material Accountancy for Reprocessing Plants

The statistical treatment of sequential MUF data has become highly sophisticated and the relevant literature huge,[7] although research has been narrowing the alternative tests down to a few.[8] Statistics derived from the sequences of data are tested against the hypothesis that a diversion has taken place.[9] The detection sensitivity of different tests varies with the diversion scenario (a test known as Page's test allows parameters to be adjusted to improve the sensitivity for one type of diversion over another), and no single test is most sensitive to detecting all types of protracted and abrupt diversions.

One saving feature, however, is that:

> ...detectionof the gross falsifications necessary to conceal an assumed abrupt diversion can be separated from the problem of the detection of a series of small falsifications which might conceal an assumed protracted diversion. In the former case, verification must be timely but need not be highly accurate [since the diversion is so large]; while in the latter case, it must be highly accurate but need not be timely [since the diversion takes place over sufficient time that it will be detected before a significant amount is lost]. There are no verifications which must be both.[10]

So far, NRTA has been investigated primarily at relatively small plants, such as Japan's Tokai reprocessing plant, with a throughput of 90 tonnes heavy metal per year. However, it is also being explored at the large British THORP reprocessing facility. In addition to periodic recalibration of measurement systems, it requires a "clean" set of data free from diversion or corruption, including freedom from an operator's intentionally widening MUF values by adding and subtracting material randomly during the calibration period. IAEA's plans for addressing this latter problem include scrutinizing any sequence of MUF values that is large-not only when compared to the expected Target Values, but also to those generated by similar plants operating in other countries. " However, the total number of such plants is very small, most of their designs unique, and the amount of experience in interpreting such comparisons virtually nonexistent. **Thus, there may be considerable uncertainty in the ultimate performance of NRTA methods at large plants for some time.**

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[7] An overview is given in Lovett, op. cit., pp. 111-135, and references 181-188 and 202-203 therein. Other representative articles are R. Beedgen and R. Seifert, "Statistical Methods for Verification of Measurement Models, " and Barry J. Jones, "Near Real Time Materials Accountancy Using SITMUF and a Joint Page's Test: Comparison with MUF and CUMUF Tests," both in *ESARDA Bulletin, No,* 15, November 1988, pp. 5-8 and 20-26; and M. Delange, "The Cumulated Flux Verification Approach ," in *Proc. Third International Conference on Facility Operations-Safeguards Interface,* San Diego, CA, Nov. 29-Dee. 4, 1987 (La Grange Park, IL: American Nuclear Society, 1988), pp. 222-229.

[8] Two such tests are known as Neyman-Pearson with test statistic CUMUF, and Page's test. The mathematics of Page's test are complex, but the concept is not. Rather than examining the absolute magnitude of CUMUF (the cumulative value of the MUF summed over the various material balance periods), it examines the *slope* of a line describing the CUMUF data. At any point, the test asks whether the most recent point is consistent with past data, in such a way that recent data is given more weight than older data. Lovett, op. cit., p. 132. In other words, a sequence of cumulative MUF values in the absence of real loss would be expected to "random walk" away from a zero value at a rate proportional to the square root of the number of MUF values used in the sum, but no faster than this. By mathematically adjusting the CUMUF data to eliminate the effect of this expected wandering away from zero, one would expect a best-fit line in the absence of loss to have zero adjusted slope. The actual slope is then compared and tested for statistical significance using Page's test. See also R. Beedgen and R. Siefert, "Statistical Methods for Verification of Measurement Models," *ESARDA Bulletin, No. 15,* November 1988, pp. 5-8.

[9] Another statistical test, know as the Kalman filter, is a technique for obtaining a "best estimate" from a sequence of MUF data of the amount of loss that has taken place per period. However, it is not useful from a safeguards perspective, because it fails to indicate whether MUF data require further investigation. That is, it does not indicate whether the "best estimate" loss is significantly different from zero, given uncertainties in measurement.

[10] IAEA, TASTEX, *Tokai Advanced Safeguards Technology Exercise,* Technical Report Series No. 123 (Vienna, Austria: IAEA, 1982), p. 111.

[11] Target values represent the expected current performance—in terms of achievable uncertainty limits—of various measurement techniques. See P. De Bievre, "Random Uncertainties in Sampling and Element Assay of Nuclear Materials Target Values 1988, " *ESARDA Bulletin, No. 13,* October 1987, pp. 8-16.

BOX A-1 (Cont'd.): New Approaches to Material Accountancy for Reprocessing Plants

The ultimate detection sensitivity of NRTA for *abrupt* diversion has not been precisely defined, and indeed cannot be except in terms of a specific reprocessing plant and its specific measurement procedures. There has been some speculation among safeguards experts that an 8 kg abrupt diversion detection goal may be achievable, even in the larger (800 t/yr) plants, but at least one study (albeit one about a decade old) claimed a limit no better than about 17 kg plutonium, and 24 kg for protracted diversion.[12] Another estimated that while NRTA might be able to lower detection thresholds by as much as an order of magnitude from conventional material accountancy, such levels still amounted to uncertainties of 15 to 30 kg of plutonium.[13]

In any case, a considerable body of statistical data—more than 50,000 paired sets of data of IAEA and operator measurements from a variety of types of bulk-handling facilities—are already being accumulated and analyzed by the IAEA. The variation of this data about its own mean provides a statistically valid estimate of the total random error in its underlying measurement data, and the difference between its mean value (over some period) and zero is a useful estimate of the net total of all uncorrected measurement biases. Statistically, much can be done with such data to evaluate the *qualify* of measurement systems themselves, which is critical both for evaluating and improving overall material accountancy. Some statisticians object to such a global approach, arguing in favor of a systematic measurement-by-measurement analysis (allowing traditional error propagation studies). However, given the amount of data that NRTA methods are expected to produce, an approach based on analyzing historical data appears to hold some promise.

[12] D. Gupta et al., "Investigations on Detection Sensitivity of the NRTA Method for Different Size Reprocessing Facilities," Kernforschungszentrum Karlsruhe, KfK 4017, December 1985, as cited in Lovett, op. cit., pp. 200, 203. The test for protracted diversion is based on Page's test.

[13] R. Avenhaus et al., 'Comparison of Test Procedures for Near-Real-Time-Accountancy," 6th ESARDA Symposium, Venice, May 14-18, 1984.

guarded and can only be entered by those possessing the right keys and codes.[7] Diversion at points early in the process area, after the spent fuel is dissolved in hot nitric acid but before the fission products are removed, would be difficult because of the intense radioactivity and low plutonium concentration of the solution. At this stage in the process, for instance, there might be only 2 g plutonium per liter of solution, requiring thousands of liters to be bled off to divert 1 significant quantity (SQ) of plutonium.[8]

The latter scenario would require the solution to be transported through additional pipes, valves, or other means to a shielded location outside the material balance area and to be clandestinely replaced with alike quantity of plutonium-depleted solution. It would also require that material accountancy methods fail to detect the missing plutonium. Early submission of plant design information to the IAEA and its subsequent verification during the construction of large plants is thus a key element in helping to rule out such

[7] Berkhout and Walker, op. cit., footnote 5, p. 7. These measures guard against theft, but not diversion commited by the plant operator.

[8] Plutonium concentrations increase as the process streams proceed through the plant. For example, to remove 8 kg of plutonium would require diverting about 4,000 liters of solution from the dissolver, about 800 liters from the last extraction cycle, or 30 to 40 liters from the concentrated evaporator liquor. J.E. Lovett, "Nuclear Materials Safeguards for Reprocessing," International Atomic Energy Agency Report STR-151/152 (December 1987), p. 161.

diversion scenarios. The better a plant design is understood, the more confidence the IAEA would have in ruling out undeclared diversion paths. This aspect of "safeguardability," in fact, is being taken very seriously in the design and construction of new plants.

Tests to be carried out during cold commissioning (i.e., with the use of unirradiated reactor fuel in lieu of actual spent fuel) and hot commissioning (i.e., with actual spent fuel, which is intensely radioactive) will also confirm the physical verification of plant systems and establish baselines for comparing future observations. However, given the complexity of large reprocessing plants, involving multiple buildings, underground pipes, many large storage tanks, and inaccessibility of various radioactive process areas once operating, IAEA experts and others admit that such verification can never completely rule out the possibility of hidden design features. The IAEA nevertheless claims that by carefully examining the operation of the plant, including the flows and material balances, during commissioning tests and *over extended periods of time in near-equilibrium conditions*, it is able to further verify the plant design parameters, making diversions from the process area more likely to be detected.

The intense radioactivity of the spent fuel being reprocessed mandates that radiation shielding be placed around process operations areas in a reprocessing plant. This shielding facilitates increased use of C/S techniques. However, containment of the process area is not absolute, since lines must carry the spent fuel and other chemicals into the process area and carry the plutonium product and various wastes out. Numerous steam, vacuum, and instrumentation lines also penetrate the shielding. (In general, though, both the intense radiation and the corrosive nitric acid environment inside the shielded process area dictate that nothing be placed inside the shielding if it is feasible to leave it outside.) The total number of shielding penetrations in a large reprocessing plant is in excess of 1,000, including buried pipes to adjacent process buildings and to waste storage tanks. Design verification is essential to ensure that pipes suitable for plutonium transfer are identified and controlled.[9]

Once a plant is operating, the experience of the inspectors in understanding the plant operating history becomes increasingly important in interpreting measurement results. For this reason, it is very important to include some inspectors with industrial reprocessing experience. Safeguards experts point out that when various statistical tests are applied to a sequence of process control data and to measurements taken at various points in the plant, and these measurements are combined with a thorough understanding of the plant's designed operating conditions, sensitivity to diversion detection improves over the case in which only annual material balance measurements are used. **Nevertheless, no single statistical test is best suited to detecting all types of abrupt and protracted diversion scenarios, and there is little practical experience in directly applying these tests to large plants.[10]** Furthermore, there remains considerable disagreement over the extent to which more sophisticated statistical tests will be able to improve the uncertainties over simpler methods. The ultimate constraint is measurement uncertainty, rather than statistical analysis methodology.[11] Experience to be gained by EURATOM in safeguarding the large THORP reprocessing plant (in the United Kingdom) will be useful in assessing these advanced data analysis techniques. Furthermore, the problem is more difficult both for older plants, whose measurement

[9]Ibid., p. 213.

[10]*Abrupt* or *protracted* refers to the rate at which plutonium is surreptitiously removed from the plant. Use of multiple tests could be one way to test for different types of diversion, but doing so can artificially increase and complicate the calculation of the false alarm rate.

[11]See, e.g., Marvin Miller, "Are IAEA Safeguards on Plutonium Bulk-Handling Facilities Effective?" *Nuclear Control Institute*, August 1990, p. 5.

systems may not be as reliable or as comprehensive as would be needed to thoroughly understand plant operation, and for larger plants, whose large throughput increases the size of measurement uncertainties. (Fortunately, there are very few large reprocessing plants outside nuclear weapon states.)

In addition to the need for accurate and precise material-accountancy measurements, the IAEA also requires accurate estimates of measurement *uncertainties* in order to carry out its safeguards functions. If uncertainties were overestimated, the utility of measurements for detecting actual losses would decline, while if the uncertainties were underestimated, excessive numbers of false alarms would be generated. There have been extensive efforts over the years to make scientifically defensible estimates of measurement uncertainties based on actual plant operating experience. Nevertheless, most of these so-called collaborative analysis programs have involved measurements on well-behaved, well-characterized materials (e.g., product materials) that have not been irradiated. Furthermore, samples taken for analysis by such programs are often given special attention by the best available analysts, which may not be the case for safeguards during routine plant operations.[12]

The Working Group on Techniques and Standards for Destructive Analysis of the European Safeguards Research and Development Association (ESARDA) has issued lists of "target values" that laboratories should be able to achieve on a routine basis—or that in some cases "must be met in the near future if the large material throughput of the new reprocessing plants under construction is to be adequately safeguarded."[13] Some of these are given in table A-2.

Based on a simple numerical argument using these uncertainties—and barring acquisition of additional measurements and use of more sophisticated statistical analysis—many analysts have concluded that measurements are incapable of reliably detecting diversions of one or even several significant quantities of safeguarded material from large reprocessing plants.[14] The reasons for this are twofold. First, random and systematic measurement uncertainties (relative standard deviations) for many of the techniques used to verify material inventories in bulk-handling facilities are at best on the order of a few tenths of a percent, and some are as large as a few percent or more. At large plants, this fraction of annual plutonium throughput is considerably larger than 1 SQ. For example, table A-3 shows that a large reprocessing plant with a nominal measurement uncertainty of 1 percent and an annual capacity of 800 tons of spent fuel per year will have an uncertainty in plutonium throughput of 64 kg. Under conventional material accountancy calculcations, a diversion would have to be 3.3 times this amount—211 kg, or 26 SQ—before there would be a 95 percent probability of detecting it, assuming that false alarm rates were to be kept under 5 percent. Even improving measurement precision by a factor of five in this example would lower the corresponding diversion threshold to 5 SQ.

[12]Ralph Gutmacher, "Measurement Uncertainty Estimates for Reprocessing Facilities," Los Alamos National Laboratory Report LA-11839-MS (ISPO-315), October 1990, pp. 1-2.

[13]See P. De Bievre et al., "Random Uncertainties in Sampling and Element Assay of Nuclear Materials. Target Values 1988," ESARDA Bulletin, No. 13, October 1987, pp. 8-16.

[14]See, e.g., Miller, op cit., footnote 11.

TABLE A-2: Principal Sources of Plutonium Measurement Errors in Reprocessing Plants

Sampling/measurement point	Instrument or method	Measurement	Goal for onsite lab (percent relative)	Overall target values (percent relative) Random	Systematic
Head end/separation stage					
Input tank solution	HKEDG	Plutonium concentration	=< 1	0.6	0.3
Buffer/feed tanks	IDMS	Plutonium concentration	=< 0.2	0.2- 0.4	0.1 -0.2
Scrub and waste tanks	Pu(VI) spectro.	Plutonium concentration	=< 25		
MOX conversion					
MOX canisters	NDA in plant	Plutonium concentration; total plutonium	1		
MOX canning	KEDG	Plutonium concentration	=<0.2		
Product area					
Plutonium oxide powder	T/C	Plutonium concentration		0.15	0.15
	HLNC	Total plutonium		1.0	0.5

KEY: HKEDG = hybrid k-edge densitometer; IDMS = isotope-dilution mass spectrometry; Pu(VI) spectro. = spectrophotometry; NDA = nondestructive assay (e.g., can include HKEDG, KEDG, and HLNC); KEDG = k-edge densitometer; T/C = titration/coulometry; HLNC = high-level neutron coincidence assay.

SOURCE: Adapted from Thomas Shea et al., "Safeguarding Reprocessing Plants: Principles, Past Experience, Current Practice and Future Trends," *Journal of Nuclear Materials Management,* July 1993, pp. 22,25.

Second, actual IAEA experience in safeguarding large plants is minimal, so that it is not known how well routine measurements will compare with their predicted performance.[15] Thus, while one analysis of the THORP facility, for example, concluded that the uncertainty inclosing the annual plutonium balance following a plant washout should be about+ 6.7 kg (1 σ) and that the uncertainty in determining in-process inventory should be about+ 2 kg, it further noted that these precisions are design targets and may not necessarily be achieved.[16]

[15] The six reprocessing facilities under IAEA safeguards at the end of 1992 were the DPRK's "radiochemical laboratory" (where reprocessing activities have since been suspended, but where North Korean unwillingness to allow the IAEA to determine the extent of previous reprocessing operations constitutes a violation of safeguards obligations); WAK in Germany (being decommissioned); PREFRE in India (where only stores of recovered PuO_2 are safeguarded, not the chemical parts of the plant); EUREX and ITREC-Trisaia in Italy (now shutdown); and Tokaimura in Japan. IAEA Annual Report for 1992, p. 161. None of these qualifies as a "large" reprocessing plant. (See table A-1.)

[16] R.D. Marsh et al., "Effective Safeguards in a Commercial Reprocessing Plant," in Proceedings of the Third International Conference on Facility Operations--Safeguards Interface, San Diego, CA, Nov. 29-Dee. 4,1987 (La Grange Park, IL: American Nuclear Society, 1988), p. 46. Note that to achieve a 95 percent detection probability with 5 percent false alarm rate requires a diversion of 3.3 σ, which in this case would be almost 3 SQ. (See Box 3-4 in the main text, chapter 3.)

TABLE A-3: Annual Plutonium-Throughput Uncertainties in Reprocessing Plants[a]

Nominal measurement uncertainty	Small reprocessing plant[b] (30 t HM/yr[c])		Medium reprocessing plant[d] (100 t HM/yr)		Large reprocessing plant[e] (800 t HM/yr)	
	Monthly	*Yearly*	*Monthly*	*Yearly*	*Monthly*	*Year/y*
0.2 %	0.04	0.48	0.13	1.6	1.1	12.8
1.0%.	0.2	2.4	0.67	8.0	5.3	64

[a] Uncertainties given in kilograms of plutonium, assuming 0.8 percent plutonium by weight in spent fuel (nominal average of commercial spent fuel from a mixture of 80 percent light-water reactors and 20 percent heavy-water "CANDU" reactors). Plutonium concentrations can range from under 0.1 percent in very low burnup fuel to about 1 percent in high burnup spent fuel from commercial LWRs.

[b] Similar in size to reprocessing facilities at Karlsruhe (Germany), Mol (Belgium), Saluggia (Italy), and Trombay (India). (See table A-1 for safeguards and operational status.)

[c] t HM/yr = tonnes of heavy metal (spent fuel) processed by the Plant per year

[d] Similar in size to reprocessing facilities at Dimona (Israel), Tarapur (India), Tokai-mura (Japan), and one that had been planned in the late 1970s at Chasma (Pakistan).

[e] Similar in size to reprocessing facilities at Cap de la Hague (France), Chelyabinsk-40 (Russia), Rokkasho-mura (Japan), THORP (United Kingdom), and one that had been planned for Wackersdorf (Germany).

Note that if these represent one standard deviation uncertainties in MUF determinations, then the amount of diverted plutonium that could be detected with a 95 percent detection probability and a 5 percent false alarm rate-the nominal safeguards goal—is 3.3 times the amount given in the table Diversions of one times the amount could also be detected, but with only about 26 percent probability if the 5 percent false alarm probability is to be maintained. See E.A. Hakkila et al., *Materials Management in an Internationally Safeguarded Fuels Reprocessing Plant,* vol. 1. Los Alamos Scientific Laboratory, Report LA-8042, April 1980, p. 8.

SOURCE: Office of Technology Assessment, 1995.

DIFFICULTIES AND LIMITATIONS IN IMPLEMENTING SAFEGUARDS

Experts within the IAEA claim that none of the problems associated with safeguarding reprocessing plants has precluded inspection goals from being attained, yet they concede that "improvements are needed to improve the technical credibility of the safeguards applied, or to lower the costs of safeguards implementation without adversely affecting safeguards effectiveness."[17] Many critics feel that the "inspection goals" being referred to in such statements are not as credible as they should be in providing strong assurances against diversion of significant quantities of material. 18 On the overall feasibility of safeguarding large plants, opinions range from strong skepticism to bold confidence. In the words of one of the more skeptical experts,

> In existing large facilities of this capacity and complexity, amounts of fissile materials that are single-weapon significant can be lost in the maze for months, and some in operations will know how to take advantage of this for diversion. Without the best in data and statistics, the problem is impossible. With the best in statistics the problem has not yet been resolved. Even those who operate a large reprocessing facility with the best of intentions will not know where significant amounts of materials reside all the time and will not be able to detect small continu-

[17] Thomas Shea et al., "Safeguarding Reprocessing Plants: Principles, Past Experience, Current Practice and Future Trends," *Journal of Nuclear Materials Management,* July 1993

[18] Inspection goals refer to the ability of inspectors to meet "safeguards criteria" for a given type of plant. These criteria consist of a detailed list of specific actions that must be carried out, including the records to verify, items to identify, count, or check for integrity (within various agreed levels of confidence), C/S measures to evaluate, measurements to take, and so forth. The procedures to meet these criteria are negotiated and set forth by the IAEA and the state as part of the Facility Attachment for each given plant.

ing diversion by persons familiar with the plant.[19]

IAEA officials knowledgeable on the subject claim that such plants are indeed "safeguardable." In making such a claim, they refer to a number of statistical methods, such as near-real-time accountancy, that will be used to reduce overall uncertainties. Nevertheless, they also note the following current limitations of safeguards at reprocessing plants:[20]

- Biases in solution measurements, meaning readings that are either consistently above or consistently below their true value, persist at levels 10 times greater than the expected "target values" for these measurements (i.e., at greater than 1 percent). Such inaccuracies are widely agreed to be one of the principal sources of error in closing material balances in reprocessing plants.
- Determining the plutonium content of spent fuel shipped to a reprocessing plant—to be compared with the plutonium content recovered via reprocessing—is problematic. The plutonium content of the fuel as it leaves the reactor is calculated, not measured; moreover, these calculations are inaccurate, particularly for boiling water reactors. In addition, batches of fuel with different plutonium content and from different types of reactors are often mixed during head-end operations at a reprocessing plant. Thus, improvements are required in the analysis of differences between plutonium content as declared by the shipper and as measured by the recipient (so-called shipper-receiver differences, or SRDs).[21]
- Sample preparations at the facility, shipping of samples to the IAEA Safeguards Analytical Laboratory, and sample analysis and evaluation can take up to three months.
- In some cases, it is not possible to assure that samples taken for the IAEA are not altered prior to shipment to the agency's laboratory. This uncertainty can undermine confidence in the safeguards regime for a reprocessing plant.
- Continuing verification of design information for operating plants (as recommended by the IAEA Board of Governors) will require significant effort and may interfere with plant schedules. Limitations caused by radiation once a plant begins operating will inhibit the ability of inspectors to conduct physical verification.

The plants examined by LASCAR are designed to process spent fuel in quantities about four times larger than those of plants built in the 1970s[22] and involve plutonium throughput, in-process inventory, and storage capacity 10 to 50 times the levels encountered in existing plants *under IAEA safeguards*.[23] Experts acknowledge that a considerable effort will be required to translate the LASCAR recommendations into specific working

[19]John M. Googin, senior staff consultant, Oak Ridge National Laboratory, private communication, September 1993.

[20]See, e.g., Shea et al., op. cit., footnote 17, pp. 24-26.

[21]An alternate view is that the problem of determining plutonium content of spent fuel assemblies is not important if there is proper item accountancy of the assemblies, together with continuity of knowledge over the assemblies until their dissolution. In other words, if all the spent fuel—and hence all the plutonium it contains—ends up in the reprocessing plant, it does not matter how well the plutonium content is known before its first measurement in the reprocessing plant's front end. However, although maintaining item accountancy of the spent fuel would suffice to assure lack of diversion before the material enters the head end of the plant, an accurate, independent estimate of the plutonium content in the spent fuel would provide an additional check against diversion before the fuel's plutonium content had been measured. It would also provide an independent measurement to complement the assay made once the plutonium is in solution.

[22]LASCAR report, op. cit., footnote 3, p. 1.

[23]EURATOM has some experience in safeguarding large British and French reprocessing plants, but their experience and specific approach are independent and not shared with the IAEA.

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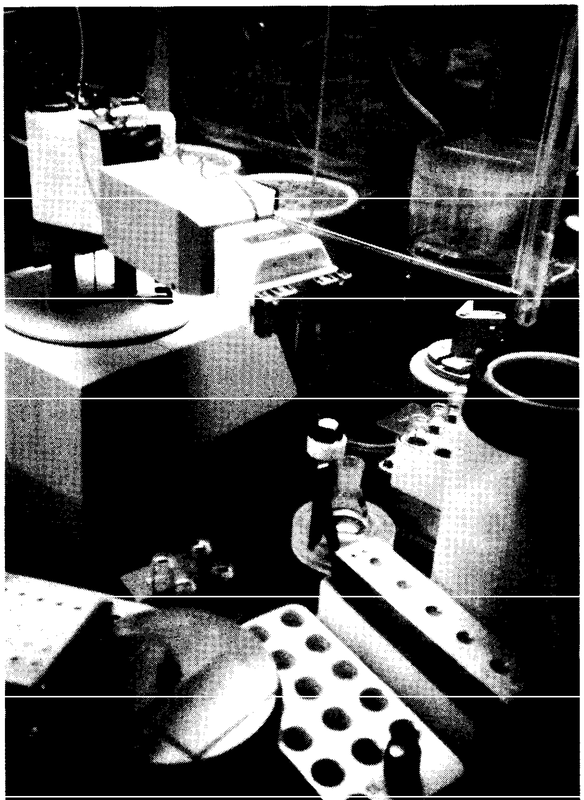

Robotic analysis of plutonium-containing samples at the IAEA's Safeguards Analytical Laboratory near Vienna. Use of onsite laboratories at reprocessing plants can eliminate delays due to packaging and shipping samples to Vienna for analysis.

arrangements at new reprocessing facilities. Problems associated in particular with safeguarding such large reprocessing facilities are the following:[24]

- Even if target values for measurement uncertainty are achieved, technologies to account for the total amount of plutonium processed by such a plant are insufficient for the anticipated needs, since the 0.1 percent uncertainty target for annual throughput may be greater than 1 SQ of plutonium. (Box A-2 describes various measurement techniques associated with reprocessing plants, and table A-3 translates various percentage measurement uncertainties into uncertainties in plutonium throughput for different size plants.)
- Monitoring of process operations will be required in real-time, an arrangement more intrusive and requiring more frequent inspector inquiries than at present, unless some sort of remote monitoring is employed.
- Costs for implementing safeguards at these new reprocessing plants will be substantial, requiring additional resources for staff, equipment, and operations, and straining the limits of IAEA verification capabilities. For example, roughly 45 inspectors will be needed to implement safeguards at each of the THORP and Rokkasho facilities (see box A-3 on inspection efforts), while the current IAEA inspectorate has only about 200 inspectors and inspection assistants on which to draw. This issue remains unresolved.
- New plants may employ new types of equipment (e.g., continuous dissolvers, centrifugal contractors and continuous evaporators), requiring new inspection procedures. Specialized verification systems will tax the IAEA's ability to ensure reliable safeguards implementation unless aided by support from member states through programs with the cooperation of the plants' operators.

Within the LASCAR forum and elsewhere, however, much work has been done during the last five years to address these problems. There are several methods being implemented or considered for larger reprocessing plants:

- Expanded use of unattended verification arrangements, telecommunications, and resident inspector deployment as possible efficiency measures. (Resident inspectors will substantially reduce the inspector staffing requirements, but will require "attractive arrangements" to bring inspectors to live in remote areas.)

[24] Shea et al., op. cit., footnote 17, pp. 24-26.

BOX A-2: Measurements Associated with Reprocessing Plants

Measurement Categories ***(WHAT is measured):***

- *Input and output solutions and solids:* concentration; isotopic composition; volume, density, or weight
- */n-process inventory:* as above, for solutions
- *Wastes:* leached hulls (short lengths of fuel-rod cladding after the fuel itself has been dissolved away); other wastes, such as centrifuge sludge (the undissolved solids removed by a centrifuge from the spent-fuel dissolver solution)

Measurement techniques ***(HOW measurements are made):***[1]

- *Alpha spectrometry and isotope-dilution alpha spectrometry.* Measures radioactive alpha particles emitted by plutonium; measures the total plutonium in dissolver solutions, if the plutonium isotopic composition is known from other measurements.
- *Calorimetry.* Measures heat generated by radioactive decay; primarily used for plutonium oxide product material, when plutonium isotopic concentration and americium-241 content are known from other measurements,
- *Chemical titration.* Measures electrical properties of a solution containing a compound that undergoes a chemical reaction (e. g., changes valence states) while precisely measured amounts of another chemical are added; used to measure uranium and plutonium concentrations in dissolver solutions and product material; relative accuracies of 0.05 percent to 0.1 percent can be achieved at, for example, IAEA's Safeguards Analytical Laboratory at Siebersdorf.
- *Gamma-ray spectrometry* Measures the energy of gamma rays produced by a specific type of radioactive decay (e.g., with resolutions of ±600 eV at 94 to 104 keV energy levels, which are relevant to plutonium isotopes); used to measure the concentration and isotopic composition of plutonium in product solutions or in solid form.
- K-edge *absorption densitometry.* Measures the absorption of x-rays generated by cobalt-57 and selenium-75 sources whose energies are close to the point at which plutonium absorbs x-rays most strongly (e.g., around 110 to 120 keV); used for plutonium concentrations in product solutions, input solutions, and process solutions (in-line measurements); machines cost around $300,000-$400,000 and are to be installed in the field at Tokai and Rokkasho.
- *Manometers and vibrating-tube densimeters.* Measures mass and density properties of liquids; used for measuring the densities of solutions containing nuclear materials and for calibrating tank volumes. Electromanometers are used for on-line measurements.
- *Neutron techniques.* Can be either passive and active; measure neutron emissions from various materials, such as uranium, fluorine, and chlorine, to determine their content in samples.
- *Spectrophotometry* Determines the plutonium concentration of a solution by measuring light transmitted through it at a wavelength which is absorbed by plutonium. This technique is widely used for process control and material accountancy at all stages of the process, but less frequently used for safeguards purposes.
- *Uranium gravimetry.* Used to measure mass of uranium in product.

(continued)

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[1]See e.g., Ralph Gutmacher, "Measurement Uncertainty Estimates for Reprocessing Facilities, " Los Alamos National Laboratory Report IA-1 1839-MS (ISPO-315), October 1990, pp. 14; and G. Robert Keepin, "State-of-the-Art Technology for Measurement and Verification of Nuclear Materials," in Kosta Tsipis et al. (eds.), *Arms Control Verification: The Technologies that Make it Possible* (Washington, DC: Pergamon-Brassey's, 1986), pp. 323-337.

BOX A-2 (Cont'd.): Measurements Associated with Reprocessing Plants


DEPARTMENT OF ENERGY

Mass spectrometer at the IAEA's Safeguards Analytical Laboratory

- *Mass spectrometry and isotope dilution mass spectrometry.* Measures the mass of ionized particles passed through a magnetic field; widely used for determining uranium and plutonium concentrations, and especially for isotopic composition (e.g., of samples containing isotopes ranging from uranium-233 to plutonium-242); current machines at the IAEA's Siebersdorf Laboratory can characterize microgram samples routinely; machines appropriate for clean-room facilities can characterize micron-sized particles containing only on the order of picograms (10-12 grams) of material.[2] Cost can be around $1 million for each device.
- *X-ray fluorescence.* Measures well-characterized emissions from various elements (ranging from sodium to the highest elements on the periodic chart) when they are stimulated by x-rays; has microgram detection limits and gives rough estimate of amounts of each element present (but not individual isotopes); primarily used as online instrumentation for process solutions for accurate determination of plutonium/uranium ratio; often used in combination with K-edge measurement to determine plutonium/uranium ratio in low concentration solutions, for example, in plutonium dissolver solution.

[2] David L. Donohue, head of the Isotope Analysis Unit, IAEA Safeguards Analytical Laboratory, Siebersdorf, Austria, Private Communication, Oct. 20, 1993.

- The use of onsite laboratories to eliminate delays in sample analysis, ensure integrity of the samples once taken, and achieve verification measurements of the main nuclear materials streams with accuracies on the order of 0.1 percent.
- Extensive use of NRTA methods for estimating in-process inventory on a timely basis.
- Greater use of data provided by the operator, appropriately authenticated, where it would be impractical for the IAEA to implement completely independent measurement or surveillance systems.

These measures will certainly improve safeguards capabilities over current practice. **However, the application of safeguards to such large-scale plants is unproven, at least pending more experience from safeguards application at UP-3 in France and THORP in the United Kingdom.**

BOX A-3: Routine Inspection Effort at Reprocessing Plants

For medium-size and large reprocessing plants, the "maximum routine inspection effort" (MRIE) ceilings are the following:

Medium reprocessing plant[1]

For spent fuel containing 0.8 percent plutonium, the nominal plutonium throughput would be 800 kg/yr, and the MRIE for such a plant as specified in INFCIRC/153 (see box 3-4 of main text) would be 30 times the square root of 800, or about 850 person-days-of-inspection (PDI)/yr. Since one PDI allows one inspector access to the plant for up to 8 hours, this would translate into continuous presence of a single inspector for about 280 days, If such a plant were operated for 250 days/yr, this level of effort would provide for a single inspector 24 hours/day during operation plus about another 100 person-days per year for additional activities.[2]

Large reprocessing plant[3]

For spent fuel containing 0.8 percent plutonium, the nominal plutonium throughput would be 6,400 kg/yr, and the MRIE = 30 times the square root of 6,400 = 2400 PDI/y. This would set the ceiling at 2 inspectors working around the clock, 365 days/yr, plus 210 PDI/yr of additional inspections. Note that providing this level of inspection would require assigning 10 inspectors to the facility, since a full-time workload for a single inspector is 40 hrs/week for 48 weeks per year, or 240 PDI per year per inspector,

[1]Throughput of 100 t HM/yr---enough to reprocess spent fuel from about 3 commercial LWRs.

[2]Thomas Shea et al., "Safeguarding Reprocessing Plants: Principles, Past Experience, Current Practice and Future Trends," *Journal of Nuclear Materials Management,* July 1993, p. 21,

[3]Throughput of 800 t HM/yr---enough to reprocess spent fuel from about 25 commercial LWRs.