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ASSESSING THE EFFECTIVENESS OF SAFEGUARDS AT A MEDIUM-SIZED SPENT-FUEL REPROCESSING FACILITY

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Abstract

In order to evaluate carefully and systematically the effectiveness of safeguards at nuclear-fuel-cycle facilities, the International Atomic Energy Agency has adopted a safeguards effectiveness assessment methodology. The methodology has been applied to a well-characterized, medium-sized, spent-fuel reprocessing plant to understand how explicit safeguards inspection procedures would serve to expose conceivable nuclear materials diversion schemes, should such diversion occur. Understanding these relations for reprocessing plants is especially important for planning safeguards inspections because of the strategic significance of the purified plutonium produced by such plants.

1. Introduction

The safeguards effectiveness assessment methodology, developed by the International Atomic Energy Agency, has been applied to a medium-sized reprocessing plant. The steps that are involved in the assessment are summarized and a simplified example of the methodology is presented in this paper.

The methodology, as described by the Agency, involves the following steps:[1]

- Stating IAEA detection goals
- Describing the facility
- Listing possible diversion paths classified by technical complexity
- Specifying inspection activities that might detect each anomaly and estimating inspector effort for each
- Estimating or calculating the probability that each inspection activity might detect a particular anomaly
- Listing follow-up activities to resolve anomalies, should they be detected
- Analyzing the effectiveness of the selected inspection activities in detecting the postulated diversion paths.

Carrying out these steps is, of course, a repetitive process, since the possible diversion paths and feasible inspection activities will be affected by the plant design, for example, and at each step of the analysis omissions, duplications, and faulty judgements may be revealed.

In the final report of such an analysis, each of the steps listed above should be clearly stated and the relationships between diversion paths, anomalies, and inspection activities clearly explained, so that the Agency can change any of the parameters or estimates as may be appropriate for specific applications.

A computer program is used to store the information used in the analysis; to list the relationships between diversion paths, anomalies and inspection activities; and to calculate the probabilities that anomalies may be detected.[2] The program assists the analyst in providing all of the necessary information in a logical and consistent manner, in assuring that inspection activities have been postulated for detection of all of the anomalies, and in making judgments as to the relative importance of inspection activities for achieving the detection goals.

2. The Reference Plant

The reference plant employs the standard Purex process and is divided into three material balance areas (MBAs). Spent fuel is received in heavy shielding casks. Assemblies are removed from the casks underwater and stored underwater in a storage pool. Assemblies are mechanically disassembled, the rods chopped, and the pellets dissolved in nitric acid. These operations take place in MBA-1.

Fission products, uranium, and plutonium are separated from one another by solvent extraction in MBA-2. Feed, products, and wastes are accurately measured in batches.

The liquid plutonium nitrate product is stored in criticality-safe tanks for ultimate shipment to a conversion facility. The uranium product could be solid UO_2, UO_3 or UF_6, which would be loaded into containers, stored on pallets, and ultimately shipped to another facility. These activities occur in MBA-3.

Hulls and hardware are placed in containers which could be stored at the plant or shipped away for burial. Radioactive liquid wastes are stored in large tanks at the site.

Figure 1 shows the major features of the plant and gives flow and inventory quantities. More detail on a similar real facility are given in the TASTEX report.[3]

3. Design Safeguards Goals

Agency detection goals are described in the IAEA Safeguards Glossary.[4] At a reprocessing plant we interpret these as summarized in Table 1.

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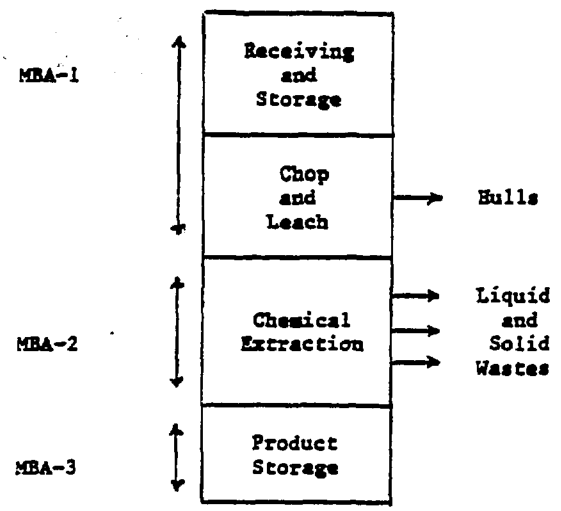

Throughput:

700 kg (U+Pu)/day
210 metric tons uranium/year
1,800 kg plutonium/year

Spent Fuel Storage:

233 PWR assemblies or
550 BWR assemblies

Product Storage:

1,000 kg plutonium in solution
105 metric tons uranium in UO_3

Fig. 1 - Schematic diagram of the reference reprocessing plant.

Table 1

REPROCESSING PLANT INSPECTION GOALS

Goal Quantity	Material Form	Detection Time	Detection Probability
8 kg Pu	Pu nitrate solution	1-3 wks	0.9 to 1.0
8 kg Pu	Spent fuel	1-3 wks	0.7 to 0.9
75 kg U-235	U-nitrate, (low-enriched)	1-3 wks.	0.7 to 0.9
75 kg U-235	U compounds in MBA-3 (low-enriched)	$\lesssim$1 year	0.7 to 0.9

The timeliness goal for plutonium in the spent fuel is the same as that for plutonium in the purified nitrate solution because the spent fuel can be reprocessed at the plant in a few days.

The timeliness goal for the low-enriched uranium before it reaches sealed storage is also the same as that for plutonium in nitrate solution because it would be useful to compare frequently the flows and inventories of uranium to those for plutonium as a means to detect diversion of plutonium from the process MBA. However, a timeliness goal of one year or less is appropriate for the uranium product stored under seal in the product storage MBA.

It should be noted that these are design goals, not requirements.[5]

4. Simplified Example: Application of the Methodology to MBA-2 of the Reference Reprocessing Plant

4.A. Diversion Paths

The term "diversion path" is defined in the IAEA Safeguards Glossary.[4] A diversion path may include the following elements: material description, location of the material, physical removal route, route of introduction of undeclared material, diversion rate, and concealment methods. The methodology also requires that the technical complexity be specified, i.e., the type and amount of effort that a hypothetical diverter would need to expend in order to perform and to attempt to conceal each of the postulated diversion paths.[1] However, technical complexity will not be discussed further here.

The most important diversion paths from the chemical processing area, MBA-2, involve the diversion of the separated and purified plutonium nitrate solution. It is assumed that the facility operator could remove plutonium nitrate solution from the process without being observed by the inspectors. The different diversion paths, then, involve the different possible concealment methods, but do not depend on the particular removal routes. In order to conceal such a diversion, the operator might attempt to report the plutonium input as less than the actual input or to report the product transferred to storage or the amount discarded in the waste streams as higher than the actual removals from the process. Also, the volume readings or the samples to be verified by the Agency would be altered. Each possible type of diversion could be abrupt, i.e., take place in a few days, or be protracted.

It is assumed that the plant operator maintains false records and submits false reports to the Agency to mask the diversion. Thus no records or reports inconsistencies would exist and actual measurements or measurement verifications would be required by the Agency inspectors to detect a diversion.

The diversion paths, the anomalies to which they would give rise (see below), and their technical complexity are summarized in Table 2.

Three diversion paths cover abrupt diversions of plutonium-bearing solution taking less than the time between inventories for near-real-time accounting purposes, about ten days. According to path a.2.1, diversion from the process is concealed by understating the input to the process and misadjusting the volume measuring instruments or altering the analytical samples. According to path a.2.2, diversion from the process is concealed by

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Table 2

DIVERSION PATHS AND ASSOCIATED ANOMALIES

Diversion Path Identifier*	Diversion Path Description	Anomalies
a.2.1	Understate Pu input and misadjust volume instruments or alter samples; divert purified Pu product before measurement.	A201, A202 A203
a.2.2	Overstate Pu product transfers to storage and misadjust volume instruments or alter samples; divert purified Pu product.	A202, A204
a.2.3	Divert Pu solution somewhere from the process equipment.	A205
p.2.1	Analogous to a.2.1	P201, P202 P203
p.2.2	Analogous to a.2.2	P202,P204
p.2.3	Analogous to a.2.3	P205, P207
p.2.4	Overstate Pu in waste discharges and misadjust volume instruments or alter samples; divert as in a.2.3.	P202, P206

*Abrupt diversions are labeled by "a" and protracted ones by "p".

overstating the plutonium withdrawn through the product accountability tank and misadjusting the volume instruments or altering the product samples. According to path a.2.3, solution is diverted from the separation process at any intermediate point with no other concealments.

Four diversion paths cover protracted diversions taking from about ten days to the time between semiannual cleanout physical inventories, about 150 days. Paths p.2.1, p.2.2, and p.2.3 are similar to paths a.2.1, a.2.2, a.2.3, respectively, except for the time involved in the diversion. According to path p.2.4, solution is diverted from the separation process, plutonium discharged in the liquid waste is exaggerated, and the waste volume measuring instruments are misadjusted or waste samples altered.

4.B Anomalies

The term "anomaly" is also defined in the IAEA Safeguards Glossary.[4] It means an unusual observable condition evoked by a diversion. Associated with each diversion path are anomalies that could be detected by appropriate inspection activities. Table 3 lists these anomalies with the detection probability range for each. The anomaly detection probability model used is a simple product of two probabilities: one for the abrupt versus protracted distinction and another for the nature of the anomaly itself. Judgmental values are used in both cases.

Table 3

ANOMALIES

Ident.	Description	Detection Probabilities Poor Case	Detection Probabilities Good Case
A201	Gravimetric Pu assay is not equal to volumetric assay at input	.48	.76
P201		.40	.64
A202	Analytical sample alteration observed	.76	.90
P202		.64	.76
A203	Isotopic correlation anomaly detected	.48	.76
P203		.40	.64
A204	Pu transferred to storage differs in concentration or volume from the accountability product measured	.48	.76
P204		.40	.64
A205	Ten-day running physical inventory and material balance show a loss of Pu	.76	.90
P205		.64	.76
P206	Unreasonable rate of Pu discharge into waste	.64	.64
P207	Semiannual cleanout physical inventory and material balance show a loss of Pu	.16	.76

Table 2 shows the anomalies that would be evoked by each diversion path. While it is true that anomaly P207 would arise from path a.2.3, it is not listed because timeliness requirements would not generally be met if an abrupt diversion were detected at a semiannual physical inventory. Also, paths a.2.2 and p.2.2 would result in shipper-receiver differences between MBA-2 and MBA-3 if a physical inventory were taken of the latter.

4.C Inspection Activities

The inspection activities are designed to detect the anomalies associated with each diversion path. All of the inspection activities chosen are presently employed by the Agency or were investigated in the Tokai Advanced Safeguards Technology Exercise (TASTEX).[3,6]

Accounting for the receipt and storage of spent fuel assemblies in MBA-1 would be based on direct observation, supplemented by surveil-

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lance instruments to keep accurate track of the items. Some nondestructive assays of spent fuel assemblies might be employed to look for substitutes.

Because reactor estimates of the U-235 and plutonium contained in spent fuel are only accurate to about 5%, these values would not be useful for closing the material balance around MBA-1. For this reason, and in order to verify the plutonium transferred to MBA-2, it would be most important to verify continually which assemblies enter the chop-leach cell and to ensure that the associated dissolver solution is accurately measured and verified. In order to do this, (1) transfers from the pool to the chop-leach cell should be observed directly or by use of reliable surveillance instruments; (2) the taking and processing of dissolver solution samples for Agency analysis should be monitored; and (3) the Agency should perform gravimetric and isotopic correlations using plant data and its own. Falsification of the volume data would not affect the gravimetric results, which the isotopic correlation technique would support. In effect, these measurements would provide a batch-by-batch assurance that no diversion is taking place in the chop-leach cell and that the input to MBA-2 is honestly and accurately measured and reported (TASTEX Tasks J, K, and L).

At a plant of the size under consideration, the amount of plutonium discarded with the radioactive wastes should be less than 1% of the throughput; grossly inflating the plutonium sent to waste would not be credible.

There is no technique like the gravimetric which could be employed to independently verify the plutonium-product measurements. Therefore, special attention should be paid to: (1) comparing the volume measured at the product accountability tank to that received by the plutonium nitrate storage tanks when each batch is transferred; (2) carefully observing the taking and measuring of samples using the K-edge densitometer and gamma-ray spectrometry instrument (TASTEX Tasks G and H); and (3) comparing the uranium and plutonium fed into the process to the uranium and plutonium removed two or three days later.

Since it would be possible to load-up the process equipment and then to divert abruptly 8 kg of plutonium, it is proposed to employ the version of near-real-time accounting that was investigated in TASTEX Task F. Once every one to three weeks, the plutonium content of the several buffer vessels would be measured and verified by the inspectors and fluctuations of the amounts contained in the extraction stages estimated using appropriate models. This procedure should provide for timely detection of an abrupt diversion and permit the use of sequential material balance analyses, which should increase the probability of detecting a protracted diversion.

Inspection activities appropriate for surveillance of the plutonium nitrate storage tanks in MBA-3 would depend on how these tanks are constructed and operated. In this study, a combination of material accounting based on volume measurements and sample analysis and on the use of seals or surveillance cameras or both is postulated.

It is assumed that a physical inventory would be performed twice a year, which would be observed and verified by the inspectors, and that the inspectors would observe the volume calibrations of all measurement tanks at that time.

For the simplified example analyzed here, IAEA inspectors would carry out the MBA-2 inspection activities listed in Table 4. Of course an examination of records and reports would be done as well. Since, as was stated above, no inconsistencies among them would exist for the diversion paths listed, records

Table 4

IAEA INSPECTION ACTIVITIES

Ident.	Description	Anomalies
2.1	Observe tank volume calibrations	A201, P201 A204, P204 P206
2.2	Check and record every input batch volume	A201, P201 A204, P204 P206
2.3	Observe tank sampling	A201, P201 A202, P202 A204, P204 P206
2.4	Analyze some accountability samples	A201, P201 A202, P202 A204, P204 P206
2.5	Perform gravimetric and isotopic correlation analysis on every input batch	A201, P201 A202, P202 A203, P203
2.6	Verify volume and concentration of every product solution batch transferred to storage	A204, P204
2.7	Periodically analyze storage tank samples	A204, P204
2.8	Inventory process feed tanks every ten days	A205, P205
2.9	Calculate the ten-day material balance	A205
2.10	Verify semiannual clean-out physical inventory and material balance	P205, P207
2.11	Perform historical and sequential analysis of waste discards	P206
2.12	Sequentially analyze the ten-day material balances	A205, P205

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and reports examinations would detect no anomalies and are not included in Table 4. The anomalies potentially detectable by the inspection activities also appear in Table 4. Should any inspection activity detect an anomaly, discussions with the plant operator and repetitions of the activities, if possible, would be the follow-up actions to be taken to determine if the anomalies resulted from innocent causes as opposed to diversions.

5. Illustration of Results of the Analysis

After the information described above has been entered into a computer and checked for accuracy and consistency, a program performs calculations and correlations and presents the results graphically, as shown in Figures 2, 3 and 4.[2] Figures 2 and 3 present the results as bar graphs showing the estimated probability that each of the postulated diversion paths would be detected if the assumed inspection activities were to be conducted. Lower detection probabilities were assumed in the case of Figure 2, and higher probabilities in the case of Figure 3.

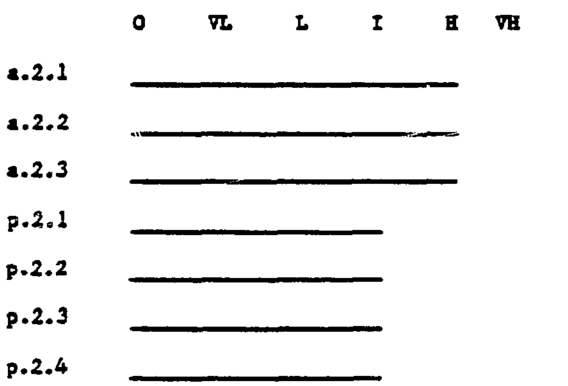

Figure 2

Diversion path detection probabilities in the case of relatively poor anomaly detection probabilities.

(VH means p$\geq$.9; H,.9>p$\geq$.7; I,.7>p$\geq$.3;

L,.3; L,.3 p$\geq$.1; VL,.1 p$\geq$0.)[1]

One qualification is important here. Sometimes, diversion paths are defined in such a way that all of the corresponding anomalies would occur given the path. It is then appropriate to set the path detection probability equal to that of the anomaly with the highest probability of detection. In the simplified example discussed here, the diversion paths are combinations of more refined paths and are not defined so that all of the anomalies would occur. Nevertheless, the same algorithm is used for the path detection probability, resulting in a generally higher path detection probability than for all but one of the more refined paths.

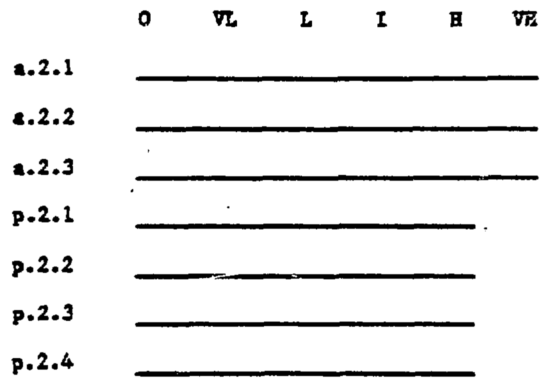

Figure 3

Diversion path detection probabilities in the case of relatively good anomaly detection probabilities.

	a.2.1	a.2.2	a.2.3	p.2.1	p.2.2	p.2.3	p.2.4
2.1	X	X		X	X		X
2.2	X	X		X	X		X
2.3	X	X		X	X		X
2.4	X	X		X	X		X
2.5	X	X		X	X		X
2.6		X			X		
2.7		X			X		
2.8			X			X	
2.9			X				
2.10						X	
2.11							X
2.12			X			X	

Figure 4

Chart showing the diversion paths (column labels) potentially detectable by each inspection activity (row labels).

Figure 4 shows that there is at least one inspection activity that is potentially capable of detecting each diversion path.

For the complete reprocessing plant analysis, there are many more diversion paths, anomalies, and inspection activities and the results are more complicated and uneven than shown in the illustrations presented here.

6. Discussion

The crucial elements of a safeguards approach for a reprocessing plant are (1) assurance that all spent fuel assemblies brought to the plant are authentic and are verifiably

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dissolved; (2) verified measurements of the plutonium input, product, and waste streams; and (3) assurance that plutonium product is not diverted from storage. Particular inspection activities studied here as part of such an approach include gravimetric confirmation of the plant's plutonium input, to detect or deter spent fuel diversions between reactors and the reprocessing plant's process MBA, and a near-real-time inventory of the materials in MBA-2, to detect or deter abrupt diversions after the input measurements.

The safeguards effectiveness assessment methodology, applied in this paper to the chemical process MBA of a reprocessing plant, allows one to determine just how well such inspection activities would serve in detecting diversions of plutonium. In the complete study, all three MBAs of the reference reprocessing plant have been analyzed in a similar fashion. The methodology is of greatest value in exposing weaknesses in inspection approaches or in comparing several inspection approaches to determine the effect on the overall safeguards effectiveness of changes in the approach.

7. References

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