AN APPROACH TO IAEA VERIFICATION OF THE NUCLEAR-MATERIAL BALANCE AT THE PORTSMOUTH GAS CENTRIFUGE ENRICHMENT PLANT (GCEP)*

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Abstract

This paper describes a potential approach by which the International Atomic Energy Agency (IAEA) might verify the nuclear-material balance at the Portsmouth Gas Centrifuge Enrichment Plant (GCEP), should that plant be placed under IAEA safeguards. The strategy makes use of the attributes and variables measurement verification approach, whereby the IAEA would perform independent measurements on a randomly selected subset of the items comprising the U-235 flows and inventories at the plant. In addition, the MUF-D statistic is used as the test statistic for the detection of diversion. The paper includes descriptions of the potential verification activities, as well as calculations of (a) attributes and variables sample sizes for the various strata, (b) standard deviations of the relevant test statistics, and (c) the sensitivity for detection of diversion which the IAEA might achieve by this verification strategy at GCEP.
1. INTRODUCTION

This paper describes a potential approach by which the International Atomic Energy Agency (IAEA) might verify the nuclear-material balance at the Portsmouth Gas Centrifuge Enrichment Plant (GCEP), should that plant be placed under IAEA safeguards as part of the US/IAEA Agreement. Certain aspects of the plant design continue to evolve and thus it may be expected that the potential approaches to material-accountancy verification may evolve also. In addition, application of the described approach is contingent in part upon the successful completion of the safeguards-instrumentation development programs which are underway at present. The potential approach does not reflect possible reductions in IAEA inspector verification activities which might be facilitated by physical access to the cascade halls, since such access has not yet been defined.

2. MATERIAL-BALANCE ACCOUNTING BY THE GCEP OPERATOR

For the purpose of this paper, we have assumed that the Portsmouth GCEP would have a nominal separative capacity of 8.8 million SWU per year. The reference plant is based on the following design characteristics:

<table>
<thead>
<tr>
<th>Component</th>
<th>Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Separative Capacity</td>
<td>8800 t SWU/a</td>
</tr>
<tr>
<td>Feed</td>
<td>11480 t U/a; 0.71% U-235</td>
</tr>
<tr>
<td>Product</td>
<td>2210 t U/a; 2.85% U-235</td>
</tr>
<tr>
<td>Tails</td>
<td>9260 t U/a; 0.20% U-235</td>
</tr>
<tr>
<td>Wastes</td>
<td>9 t U/a; 1.0% U-235</td>
</tr>
</tbody>
</table>

The facility operator will account for this material by performing highly precise and accurate measurements on the flows and inventories of nuclear material at the facility. The relative random and relative systematic measurement uncertainties ($2\sigma_r$, $2\sigma_s$) for operator measurements of feed, product, and tails UF₆ are anticipated to have the following values: 0.01% for cylinder weighings, 0.04% for determination of uranium weight fraction, and 0.10% for determination of U-235 weight fraction. We have calculated the expected uncertainty (standard deviation $\sigma$) for the operator's annual material balance to be $\sigma_{MUF} = 56$ kg U-235, where MUF is the material-unaccounted-for. This standard deviation would equal 0.07% of the U-235 fed annually to the plant. The IAEA expects that the standard deviation of MUF, as calculated by the operator at an enrichment plant, should be $\sigma_{MUF} = 0.2\%$ or smaller, where $\sigma_{MUF}$ is expressed as a percentage of inventory or throughput, whichever is larger. (1)
3. POTENTIAL DIVERSION STRATEGIES AND THE MATERIAL-BALANCE VERIFICATION APPROACH

For bulk-handling facilities, the operator will report his material-balance measurements and his MUF for each MBA in accordance with the safeguards agreement for that facility; the IAEA verifies the material balance declared by the operator. Because the IAEA does not have the resources to independently measure all items and thereby determine its own material balance, such verification involves the independent measurement of a statistically sampled subset of the reported items comprising the material balance, the observation (and verification) of operator measurements of other items, and the auditing of facility material-balance records and reports for completeness, formal correctness, and consistency. The operator must be able to report the nuclear-materials contents of each item (or batch), and the IAEA should be able to randomly measure any item whose content has been reported by the operator.

This structure of reporting and verification presents two potential strategies to an operator who might wish to divert material from the material balance. He could report an unfalsified material balance (accurately reporting his own measurements) and divert an amount such that the reported MUF is within the range of the uncertainty in his material balance, implying or stating that this MUF resulted from measurement uncertainties. This strategy is sometimes called "diversion into MUF". Alternatively, he might falsify his reported measurements by understating reported inputs or overstating reported outputs or inventory so as to reduce his reported MUF. The magnitude of these falsifications could lie anywhere in the range from very large to very small. For example, an operator might choose to falsify the contents of one or a few containers by large amounts and hope that the IAEA would not perform any measurements on those containers. At the other extreme, the operator might choose to falsify the contents of a large number of containers by small amounts, and hope that the IAEA would not be able to accurately and precisely measure their true contents. It is convenient to define two levels of falsification: a "defect" and a "bias". We will use the term "defected item" to denote an item whose reported U-235 content differs from its true value by an amount which is significantly greater than the combined uncertainties of the operator's measurement and the IAEA's best measurement for that item. This means that an anomaly will be very clearly indicated if the IAEA decides to measure accurately a defected item. A "bias" is a falsification by an amount smaller than a defect; thus, a bias is not detectable by the IAEA from a single measurement on an item.

The IAEA has adopted a material-balance-verification strategy which is designed to detect effectively and efficiently both "diversion into MUF" and falsifications of material-balance quantities by large and small amounts (i.e., falsifica-
tion by "defects" and "biases"). This strategy is specified in the IAEA Safeguards Technical Manual (2). It makes use of "attributes" and "variables" measurements performed by the IAEA on a randomly selected sample of the items comprising the uranium flows and inventories at the facility. An "attributes" measurement is one which may be performed quickly but which is relatively less precise and accurate; such a measurement is performed on a relatively large fraction of the items in order to detect large falsifications. An example of an attributes measurement is the non-destructive measurement of the U-235 concentration for UF6 in a cylinder by gamma-ray counting. A "variables" measurement is one which has high precision and accuracy but which is often time-consuming and expensive to perform; it uses the IAEA's most accurate measurement method for an item. Variables measurements are performed to detect small falsifications (i.e., falsifications small enough to escape detection by the attributes measurement) and to detect biases. An example of a variables measurement is the measurement of the U-235 concentration of UF6 by mass spectrometry. This two-level strategy of attributes and variables measurements is efficient because (1) the attributes test can be performed quickly, and (2) if the attributes test is performed, a diverter wishing to avoid detection would be forced to make a larger number of falsifications of a smaller size; this enables the IAEA to reduce its variables-test sample size. Thus, the two-level system would reduce the effort that must be expended in destructive analyses while maintaining the ability to detect diversion.

In practice at the GCEP, this attributes/variables approach could be used to verify the major UF6 flows (i.e., feed, product, and tails UF6). It appears that nondestructive assay (NDA) attributes measurements alone would suffice for verification of the minor UF6 flows and the waste streams, since the U-235 contained in these latter flows comprise only about 0.1 percent of the U-235 contained in the plant feed.

In addition to performing attributes and variables measurements to detect large and small falsifications, the IAEA also uses the MUF-D statistic to detect diversion strategies incorporating both "diversion into MUF" and "falsification by biasing." The MUF-D statistic is the IAEA's estimate of the MUF, corrected for biases introduced by the operator; its variance is unaffected by operator systematic error(2). This means that the IAEA can verify the material balance with a sensitivity which is largely determined by its own systematic errors.

4. POTENTIAL VERIFICATION ACTIVITIES

4.1. Verification of the Major UF6 Flows

The major flows of uranium to and from the plant will be in the form of feed, product, and tails UF6 in 9.5- and 12.5-
tonne cylinders(3). The data declared by the operator will include the U and U-235 weight for each cylinder. In order to verify these flows of U and U-235, the IAEA could verify (perhaps on a random sampling basis) the following quantities: the mass of the UF\(_6\) transferred by cylinder to and from the cascades, the U weight fraction, and the U-235 weight fraction.

In principle, the IAEA could use the attributes/variables measurement approach to verify each of the three types of measurements which, taken together, define the amount of U-235 in a cylinder. In practice, the complete attributes/variables approach might be applied only to the verification of the U-235 weight fractions.

The operator will measure the full and empty weight of every cylinder of UF\(_6\) fed to and withdrawn from the cascades; the IAEA could observe these weighings as they are performed. In addition, the IAEA could observe the facility operator calibrate the accountability scales using the facility calibration weight standards. It also appears that it might be possible for the IAEA to weigh the facility check weights (cylinder replicas) using an appropriately designed, IAEA-owned, portable load-cell-based weighing system capable of weighing 12.5-tonne cylinders. The latter activity would be contingent upon development of a suitable instrument by the IAEA and its approval by the operator.

No attributes measurements appear to be necessary for the verification of the uranium weight fraction for feed, product, or tails UF\(_6\). This situation arises since the UF\(_6\) delivered to and from the U.S. Department of Energy is required by federal regulations to be at least 99.5 wt\% UF\(_6\); that is, the uranium weight fraction must be within 0.5 percent (relative) of the nominal value 0.676. Hence, reported values of UF\(_6\) purity less than 99.5 wt\% would not be acceptable, by law, and the IAEA would need to check for falsifications and biases smaller than 0.5 percent (relative). The IAEA might send a randomly selected set of UF\(_6\) samples to the IAEA Safeguards Analytical Laboratory (SAL) for high accuracy (variables) measurement of the uranium fraction. While it appears at present that such UF\(_6\) samples should be withdrawn from the liquid phase in the cylinders, it may prove sufficient for this measurement to use samples withdrawn from the gas phase.

The IAEA could use the attributes/variables measurement approach for verification of the U-235 fraction for feed, product and tails UF\(_6\). The attributes measurements of U-235 concentration could be accomplished by means of tamper-indicating, in-line enrichment monitors installed in the feed, product, and tails piping which carries UF\(_6\) to and from the cascades. These monitors could provide attributes measurements of U-235 concentration on a 100 percent sampling basis, performed automatically. Gamma-ray monitors for this purpose have been developed.
in the U.S., and have been installed in an operating enrichment plant for test and evaluation (4-6). In addition, the IAEA could send a randomly selected set of UF\textsubscript{6} samples to the SAL for high accuracy (variables), mass-spectrometric measurement of U-235 concentration. Information available at present indicates that UF\textsubscript{6} samples withdrawn from the vapor phase are quite satisfactory for this purpose, if the cylinder has been homogenized prior to sample withdrawal. All cylinders could be vapor sampled by the operator, using a portable sampling cart, under observation by the IAEA, with the samples presented to the IAEA.

4.2. Verification of the Minor UF\textsubscript{6} Flows

The periodic removal of UF\textsubscript{6} from auxiliary cold traps will lead to the annual removal of about 60 kg U-235 in 50 Model 12B (200 kg) cylinders (3). In addition, training operations in the Centrifuge Training and Test Facility (CTTF) at the GCEP would lead to the annual transfer of about 7 kg U-235 contained as UF\textsubscript{6} in about 10 Model 12B cylinders sent to and from the CTTF. Finally, about 24 kg U-235 contained as UF\textsubscript{6} in about 1880 Model 2S (2 kg) sample cylinders would be transferred from the GCEP to the Portsmouth Gaseous Diffusion Plant laboratory for analyses. Because the amounts of U-235 transferred will be small, it appears that NDA attributes measurements of these quantities would have quite sufficient accuracy for verification purposes.

Verification measurements for Model 12B or Model 2S cylinders could proceed in the following way. At the time the operator presented a cylinder of such material to the IAEA for verification, the operator would declare the U-235 content of the container. Declared values would be included in the facility accounting records. After receiving the declaration, the IAEA would decide (on a random basis) whether to verify the U-235 contents of that particular cylinder. During the course of the year, the IAEA could select several cylinders at random for attributes measurement of the U-235 contents. The attributes verification of a selected cylinder could consist of a measurement of the weight of the full cylinder and an NDA measurement of the U-235 concentration. The NDA measurement could be performed by the IAEA with the standard gamma-ray method, using either NaI or intrinsic germanium detectors and measuring the cylinder-wall thickness by ultrasonic means.

4.3. Verification of the Waste Streams

The waste streams identified at present are anticipated to contain only small amounts of U-235. The nature and estimated annual amounts of U-235 for these expected waste streams are as follows: (a) decontamination solutions, about 13 kg U-235; (b) spent chemical-trap material, about 11 kg U-235; and (c) crated solid waste, about 8 kg U-235. The U-235 concentrations for
these streams are expected to average about 1 percent U-235. Details of the packaging (i.e., number of containers, weight, and size) for these wastes have not yet been established.

Since the amounts of contained U-235 are small, the verification approach could be similar in principle to that outlined in Section 4.2. It is anticipated that the operator may determine the U-235 content of these waste items by NDA techniques. On a random basis, the IAEA could request the operator to remeasure the U-235 content of an IAEA-selected waste item using the appropriate facility NDA instrument. To ensure the correct operation and calibration of the instrument, the IAEA could request the operator to measure the contents of an IAEA-owned waste standard prior to verification of the selected item. The IAEA could participate in the measurement of both the standard and the selected item.

4.4. Verification of the UF₆ Inventories

At the time of the physical inventory, three major UF₆ inventories would exist: (a) UF₆ cylinders in storage, (b) UF₆ cylinders attached to the cascades as feed, product, and tails containers, and (c) UF₆ cylinders undergoing sampling in autoclaves. For the purpose of the physical-inventory determination, it is anticipated that the operator will drain the contents of the product desublimers and tails accumulators to their respective cylinders.

4.4.1. Cylinders in Storage

It is anticipated that the IAEA would apply seals to the valves of sampled feed cylinders prior to storage. At the time of the physical-inventory verification, the IAEA could verify the contents of these sealed cylinders by verifying the cylinder identity and the seal integrity.

The IAEA could verify the weight and enrichment for a randomly selected subset of the unsealed cylinders in storage. The enrichment could be measured by the standard NDA gamma-ray enrichment technique with an uncertainty (2σ) in the range of 4% - 12% (relative), if intrinsic germanium detectors are used. The weights might be verified by requesting the operator to weigh selected cylinders in-place using an appropriately designed, IAEA load-cell-based weighing system, if available.

4.4.2. Cylinders Attached to the Cascades

At present, the operator plans to weigh partially full feed, product, and tails cylinders on the accountability scale at the time of the physical inventory; the IAEA could observe these weightings. These gross weights could be combined with the verified values for empty (or full) weights, U fractions, and U-235 fractions to calculate the U-235 contents of these
cylinders. For product and tails cylinders, initial values for U-235 fraction could be obtained from the in-line enrichment monitors and replaced by final values determined by subsequent sampling and IAEA analysis.

4.4.3. Cylinders Undergoing Sampling in Autoclaves

The operator will have weighed (under IAEA observation) a full feed cylinder before loading it into the autoclave for sampling. The IAEA could subtract a nominal tare weight (for that cylinder type) from the verified full weight to get a weight for the contained UF₆ that would be sufficiently accurate for verification purposes. Uranium and U-235 fractions could be obtained by analyses (at the IAEA laboratory) of samples subsequently obtained from these cylinders.

The verified mass of UF₆ contained in product and tails cylinders undergoing sampling would be known from previously verified full and empty cylinder weighings performed by the operator under observation by the IAEA. Initial values of U-235 fraction could be obtained from the in-line enrichment monitors and replaced by final values determined by subsequent sampling and IAEA analysis.

5. SENSITIVITY FOR DETECTION OF DIVERSION

The MUF-D statistic could be used by the IAEA to test for diversion of uranium and U-235 from the declared nuclear material balance. This statistic combines the operator's reported MUF with a difference statistic D which estimates the operator's biases[2]. The sensitivity of this test depends upon the standard deviation of the MUF-D statistic, which in turn depends upon (a) the IAEA's random and systematic measurement uncertainties for its variables measurements and (b) the operator's random measurement uncertainties. Thus, in order to estimate the IAEA's sensitivity for detection of diversion, it is necessary to specify values for the uncertainties in its variables measurements. It is necessary also to specify the uncertainties in its attributes measurements, since the variables sample sizes depend in part upon the standard deviations for these measurements. We have assumed that the relative systematic uncertainty (2σₛ) in the IAEA's mass-spectrometric (variables) measurement of U-235 weight fraction for feed, product, and tails material will be 0.10%, due to uncertainties in the reference standards; we have also assumed that the relative random uncertainty (2σᵣ) in these measurements will be 0.10% for product and feed materials, and 0.15% for tails material. In addition we have assumed that the relative systematic and random uncertainties (2σₛ = 2σᵣ) for the IAEA's variables measurements of uranium weight fraction for UF₆ will be 0.10%, if such measurements are performed. It should be noted that the variables-measurement sample sizes are chosen sufficiently large that the contribution of random measurement uncertainty
is small compared with the contribution due to systematic measurement uncertainty in the estimation of $\sigma_{\text{MUF-D}}$.

It is anticipated that the in-line UF$_6$ enrichment monitors under development by the U.S. Department of Energy for IAEA safeguards at GCEP will achieve the following relative uncertainties (2a) for the attributes measurement of U-235 fraction: 2.0% (feed), 1.0% (product), and 10% (tails). In addition, it is anticipated that the U-235 contents of UF$_6$ in Model 12B and Model 2S cylinders could (with appropriate instrumentation) be measured by the IAEA with overall relative uncertainties (2a) of 10% and 2%, respectively. Finally, it is assumed that the U-235 content of items containing spent trap material, liquid waste, and crated solid waste could be verified by the IAEA (by observation of the operator's measurements) with a relative uncertainty 2a = 40%.

We have used these assumed measurement uncertainties to calculate the attributes and variables sample sizes that would suffice for annual verification of the GCEP nuclear-material balance. These sample sizes are given in Table I and have been calculated using the methods given by Sanborn (7). In addition, we have calculated the sensitivity for detection of diversion which the IAEA might achieve at this facility using this material-accountancy-verification approach; the calculation is sensitive to the systematic measurement uncertainties assumed for the IAEA's variables measurements of uranium and U-235 weight fractions for UF$_6$ samples. The calculated IAEA detection sensitivity for an annual material balance would be 222 kg U-235; this is the amount of U-235 which, if diverted by "diversion into MUF" or "falsification by biasing", would be detected with a probability of 90% and a false-alarm probability of 5%. (The detection sensitivity corresponds to 2.93 $\sigma_{\text{MUF-D}}$ for an alarm level set at 1.65 $\sigma_{\text{MUF-D}}$.) While additional statistical tests could be used for detection of operator inflation of his random measurement uncertainties, these tests have not been included for the purpose of this paper.

This sensitivity could be achieved by variables measurements on 54 feed samples, 21 product samples, and 51 tails samples per year. This would correspond to 3.5%, 6.1% and 4.7% of the feed, product and tails cylinders, respectively, processed per year. These sample sizes also would permit the IAEA to achieve a 90% probability of detection should the operator divert 75 kg of U-235 per year by a strategy of "falsification by large or small defects." These results are summarized in Table II.
REFERENCES


### Table I

<table>
<thead>
<tr>
<th>STRATUM</th>
<th>TOTAL POPULATION OF STRATUM (ITEMS/YEAR)</th>
<th>ATTRIBUTES* SAMPLE SIZE (ITEMS/YEAR)</th>
<th>VARIABLES* SAMPLE SIZE (ITEMS/YEAR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed Cylinders</td>
<td>1539</td>
<td>---b</td>
<td>54</td>
</tr>
<tr>
<td>Product Cylinders</td>
<td>343</td>
<td>---b</td>
<td>21</td>
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<tr>
<td>Tails Cylinders</td>
<td>1078</td>
<td>---b</td>
<td>51</td>
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<tr>
<td>Model 12B Cylinders</td>
<td>60</td>
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<tr>
<td>Model 2S Cylinders</td>
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<td>2</td>
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<td>TBD</td>
<td>2</td>
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<tr>
<td>Crated Solid Waste</td>
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<td>2</td>
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</tbody>
</table>

* Calculated using the methods given in Reference (7).

b The in-line enrichment monitors at the feed, product, and tails piping automatically provide an attributes measurement of U-235 enrichment for 100% of the cylinders.

c To be determined.
Table II

TEST-STATISTIC STANDARD DEVIATIONS
AND THE
IAEA DETECTION SENSITIVITY
(ANNUAL GCEP MATERIAL BALANCE)

Test-Statistic Standard Deviations, kg U-235

$\sigma_{\text{MUF}}$ (Operator) = 56.4

$\sigma_{\text{MUF-D}}$ (IAEA) = 75.7

IAEA Detection Sensitivity
(Detection Probability = 90%, False-Alarm Probability = 5%)

<table>
<thead>
<tr>
<th>Operator Strategy</th>
<th>Detection Sensitivity (kg U-235)</th>
</tr>
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<tbody>
<tr>
<td>Falsification by Defects</td>
<td>75</td>
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<tr>
<td>Falsification by Biasing</td>
<td>222</td>
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<tr>
<td>and Diversion into MUF</td>
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