LA-UR- 10-02071

Approved for public release; distribution is unlimited.

Title: DEFINING THE NEEDS FOR GAS CENTRIFUGE ENRICHMENT PLANTS ADVANCED SAFEGUARDS

Author(s): Brian D. Boyer, Heather H. Erpenbeck, Karen A. Miller, Martyn T. Swinhoe, Kiril Ianakiev, and Johnna B. Marlow

Los Alamos National Laboratory, Los Alamos, NM, USA

Intended for: Pacific Northwest International Conference on Global Nuclear Security–the Decade Ahead

April 11-16 2010
Portland OR

Los Alamos NATIONAL LABORATORY EST. 1943

DEFINING THE NEEDS FOR GAS CENTRIFUGE ENRICHMENT PLANTS ADVANCED SAFEGUARDS

Brian D. Boyer, Heather H. Erpenbeck, Karen A. Miller, Martyn T. Swinhoe, Kiril Ianakiev and Johnna Marlow

Los Alamos National Laboratory, Los Alamos, NM, USA

ABSTRACT

Current safeguards approaches used by the International Atomic Energy Agency (IAEA) at gas centrifuge enrichment plants (GCEPs) need enhancement in order to verify declared low-enriched (LEU) production, detect undeclared LEU production and detect highly enriched uranium (HEU) production with adequate detection probability using nondestructive assay (NDA) techniques. At present inspectors use attended systems, systems needing the presence of an inspector for operation, during inspections to verify the mass and ^{235}U enrichment of declared UF_6 containers used in the process of enrichment at GCEPs. In verifying declared LEU production, the inspectors also take samples for off-site destructive assay (DA) which provide accurate data, with 0.1% to 0.5% measurement uncertainty, on the enrichment of the UF_6 feed, tails, and product. However, taking samples of UF_6 for off-site analysis is a much more labor and resource intensive exercise for the operator and inspector. Furthermore, the operator must ship the samples off-site to the IAEA laboratory which delays the timeliness of results and interruptions to the continuity of knowledge (CofK) of the samples during their storage and transit. This paper contains an analysis of possible improvements in unattended and attended NDA systems such as process monitoring and possible on-site analysis of DA samples that could reduce the uncertainty of the inspector's measurements and provide more effective and efficient IAEA GCEPs safeguards. We also introduce examples advanced safeguards systems that could be assembled for unattended operation.

INTRODUCTION

The International Atomic Energy Agency currently safeguards large LEU (<20% enriched ^{235}U) GCEPs in several countries. Currently, the IAEA uses the same basic approach to safeguard GCEPs that the Hexapartite Safeguards Project (HSP) recommended in 1983 with some enhancements in the large URENCO facilities in Europe.[1,2] However, the GCEPs safeguards approaches in China, Brazil, and Iran are different. Furthermore, the IAEA will modify the GCEPs safeguards approach in Japan for the restart of the updated Japanese GCEP plant. There is also major expansion in the use of URENCO centrifuges. Since Areva bought into URENCO technology, Areva and have a 50% share in the actual centrifuge technology but do not share plant operational technologies such as those used in UF_6 feed handling and product withdrawal. Hence, URENCO USA* in Eunice, New Mexico (URENCO/Louisiana Energy Services), Eagle Rock in Idaho Falls, Idaho (Areva), and Georges Besse II (GB II) in Pierrelatte, France (Areva) will be basically URENCO centrifuge plants with respect to the actual centrifuge technology where HSP safeguards would be applicable. It may be argued that the IAEA's application of HSP safeguards at these new facilities, which are located in Nuclear Weapons States (NWS), will demand significant resources that could be used more effectively in non-Nuclear Weapon States. However, in the spirit of nondiscrimatory safeguards[3], some type of equivalent safeguards approach is needed in France, the United States, and the other NWS. In addition, improved GCEPs safeguards approaches are needed for deployment in any State. An advanced safeguards approach should offer more effective and efficient safeguards than present HSP safeguards provide.

We shall review the basic safeguards concerns associated with LEU GCEPs before introducing our advanced safeguards systems concepts. Three principal safeguards concerns for nuclear material diversions from LEU GCEPs include:

1. Production and diversion of a significant quantity of uranium with enrichment greater than declared (in particular, HEU with $\geq 20\%$ ^{235}U),

2. Diversion of a significant quantity of declared uranium (particularly in the form of LEU product),

3. Production and diversion of LEU in excess of declared amounts (e.g., using undeclared feed).

The detection of undeclared HEU production is of greatest concern, since HEU can be directly used in nuclear weapons. Detection of the diversion or production of undeclared quantities of LEU is also crucial for two reasons. First, LEU can be further enriched to HEU either clandestinely in a LEU GCEP or in a separate undeclared facility. Second, LEU can be used to fuel a reactor for the production of plutonium. The amount of separative work, expressed in separative work units (SWU), required to enrich natural uranium to 5% ^{235}U is about 4200 tSWU. It only takes about 1200 tSWU more work to enrich that 5% ^{235}U to 90% ^{235}U. Hence, enriching LEU feedstock to HEU instead of enriching natural uranium feedstock to HEU reduces to about one-quarter the separative work required to enrich the natural uranium all the way to 90% ^{235}U (5400 tSWU). Thus, a clandestine cascade designed to produce HEU from LEU is smaller and more easily concealed than a full-scale cascade designed to produce HEU from natural uranium. The HSP safeguards approach explicitly addresses the first two diversion concerns but does not address the third concern which centers on "undeclared feed." In this scenario, an operator would bypass IAEA inspection and introduce undeclared UF_6 feedstock into a GCEP. The operator would then remove the undeclared product for use in an undeclared HEU cascade in the same facility or in a clandestine

HEU enrichment facility. The operator would ensure that his material accountancy would not reveal the undeclared feed, undeclared product, and depleted tails by falsifying the books and ensuring any discrepancies in enrichment values or material amounts would be undetectable by IAEA safeguards.[4]

The IAEA moved in recent years to cover this gap in the GCEPs safeguards approach by rolling out a new model safeguards approach which includes randomized inspections and the use of the "Mailbox" concept as safeguards tools to enable the detection of undeclared operations.[5] A field trial was held at the URENCO Gronau GCEP in Germany to examine the practicality of measures associated with this approach.[6] The field trial successfully demonstrated the concept as had earlier trials at the Portsmouth Gaseous Diffusion Plant in the 1990s to verify HEU downblending.[7,8] This paper looks at how evolving concepts of the use of unattended NDA could enhance GCEPs safeguards and facilitate a more effective mailbox system by providing remote unattended verification of the operator's mailbox declaration on a daily basis. These approaches should not only be applicable to the URENCO facilities but should be applicable to other GCEPs under safeguards or to those which may come under safeguards in the future.

The IAEA has also published its goals[9] for an advanced GCEPs safeguards system that would include implementing information-driven safeguards; remote inspections; reduced frequency and inspection effort at facilities; reduced impact on operators to support inspections; enhanced detection probability of undeclared production of LEU; and improved timeliness and efficiency of detecting HEU production. Colleagues at Oak Ridge National Laboratory have evaluated the use of remotely acquired data to trigger inspections at a GCEP in an attempt to reach the goals stated above by expert analysis of the remotely acquired data and by using the results of that analysis to draw a conclusion that an inspection is needed to investigate anomalous data from the plant.[10] Our work in this study looks at the application of some of the advanced systems under consideration, what their performance could be, and how they could help reach the IAEA's goals for advanced GCEPs safeguards.

OPERATOR'S DIVERSION SCENARIOS AND INSPECTION NEEDS

For the IAEA to have capabilities in remote and/or unattended NDA operation with automated measurements and monitoring,[11] a new generation of instruments will need development, testing and implementation. These instruments will need to be robust, improving the quality of the NDA measurements done at GCEPs. The IAEA envisions these instruments to be complemented by unannounced inspections, Additional Protocol complementary access (CA) activities, and the application of new and novel technologies.

These new instruments should attempt to decrease the uncertainties associated with NDA and DA measurements done at GCEPs because large uncertainties associated with the operator's or the inspector's measurements produce large uncertainties in the material amounts verified. For instance, an operator can divert material by having measurement uncertainties that are large enough that the material unaccounted for (MUF) over the course of the annual material balance period is big enough, compared to the throughput of the GCEP, to hide diversion of a significant quantity (SQ) in the noise of measurement uncertainties.[12] This diversion strategy is known as **diversion into MUF** and the operator can falsify records or remove all or partial amounts of UF_6 from cylinders to get a SQ of enriched material. The second diversion strategy is for an operator to remove the material without falsifying the records and to depend on the large measurement uncertainties associated with the inspector's instruments to obscure the diversion. This is known as **diversion into D** (the overall operator–inspector difference statistic) where operator–inspector difference, d_i, is defined as:

$$d_i = [O_i - I_i] / O_i \tag{1}$$

where:

O_i = Operator declaration for item i
I_i = Inspector verification measurement of item i.

If the D statistic is larger than expected, then the IAEA can detect the diversion. The IAEA also attempts to detect diversion with the MUF-D statistic, also known as the "inspector's estimate of MUF." The sensitivity of the MUF-D statistic depends on the extent of the verification of the strata, natural, enriched, and depleted uranium in GCEPs, in the four factors of the material balance equation, shown below, that defines MUF as:

$$MUF = PB + X - Y - PE \tag{2}$$

where:

PB	=	physical inventory at the beginning of the period;
X	=	sum of the nuclear-material increases into the MBA during the MBP;
Y	=	sum of the nuclear-material decreases of the MBA during the MBP;
PE	=	physical inventory at the end of the period, measured during the Physical Inventory Taking (PIT).

The MUFs are calculated for both elemental uranium and the ^{235}U isotope. The IAEA applies the uncertainties associated with the measurement system used to determine the declared amounts of material, which make up each of the above four components of the material balance equation to the item or stratum amounts to determine the uncertainty of the material balance (σ_{MUF}). The IAEA sets its limit of the error of MUF at twice σ_{MUF} ($2\sigma_{MUF}$) with a 5% chance of false alarm and the diversion alarm level at three times σ_{MUF} ($3\sigma_{MUF}$) with a 50% probability of detection and a 99.73% confidence level. The threshold of $3\sigma_{MUF}$ is set to lower the chance of false alarms of diversion. Hence, if the operator diverts an amount of material corresponding to greater than $3\sigma_{MUF}$, he will have a 50% chance of being detected.

The IAEA expects that the operator's material balance uncertainty has a combined uncertainty of one Relative Standard Deviation (RSD), δ_E, of 0.2% error, which is the smallest uncertainty expected by the IAEA in any of the bulk handling facilities.[13] It should be noted that an enrichment plant of 3000 MtSWU/yr with ^{235}U enrichment of the feed = 0.711%, product = 5.0%, and tails = 0.34%, is typical of the lower end of the base scale of the large new GCEP facilities coming on line either as new construction or older plant expansion. However, as shown in Table 1, the operators of most of these plants currently are expanding or planning to expand their capacities to 5000–6000 MtSWU/yr with Areva's GB II topping out at 8200 MTSWU/yr. Hence, for even the low uncertainty of 0.2% error in a large GCEP, there exists the possibility of the operator hiding a diversion in the noise of the uncertainties of the material balance. These uncertainties will exceed a one SQ threshold in these cases. Our analysis here spans the range of plants, as documented in Table 1, from 500 MtSWU/yr to 9000 MtSWU/yr (five cases = 500 MtSWU/yr, 1000 MtSWU/yr, 3000 MtSWU/yr, 6000 MtSWU/yr, and 9000 MtSWU/yr) and gives a rough estimate of the needs for advanced safeguards versus how conventional HSP safeguards have been implemented. Table 2 shows the yearly material and cylinder throughputs for the five cases and the yearly σ_{MUF} for each plant which in the larger plants exceeds 1 SQ. It can be seen that our effort to create the base plant and scaling up the plants by an integer number of cylinders from the base case of 500 MtSWU/yr gives a value of separative work for each of the five model GCEPs about 5% under the declared capacity of the plant. The goal of this exercise is not to evaluate plants at exactly the value of the five GCEPs but in the range of such facilities to be able to design and evaluate workable advanced safeguards approaches for large GCEPs.

It is evident that the large scale facilities such as GB II and the planned final full-scale URENCO USA*–LES plant in Eunice, NM will move 500–800 SQs of enriched LEU out the door each year. We can see that even small uncertainties in measurements can lead to multiple SQs of material possibly being diverted in the noise of verification activities. Hence, advanced safeguards should provide not only better accountancy measures for verification but process monitoring and containment and surveillance measures as assurance that material has not been diverted.

TABLE 1: Large Scale Enrichment Plants in Operation, Construction, or Planning

ENRICHMENT PLANT	CAPACITY MtSWU/yr
URENCO - Capenhurst, UK (operation)	5000
URENCO - Almelo NL (operation)	4400
URENCO - Gronau Germany (operation)	2750
URENCO - URENCO USA* - LES – base USA(construction)	1000
URENCO - URENCO USA* - LES – original final USA (planned)	3000
URENCO - URENCO USA* - LES – revised final USA (planned)	5700
Areva - GB II France (construction)	8200
GE-H GLE (LASERS) USA (planned)	3500-6000

TABLE 2: Yearly Material and Cylinder Throughputs of Facilities for Study

Nuclear	Separative Work Capacity of 5 GCEPs in MtSWU/yr				
Material Quantity	500	1000	3000	6000	9000
Feed (Cylinders/Yr)	117	234	702	1404	2106
Product (Cylinders/Yr)	59	118	354	708	1062
Tails (Cylinders/Yr)	105	210	630	1260	1890
Feed (kgU/Yr)	8.9E+05	1.8E+06	5.3E+06	1.1E+07	1.6E+07
Product (kgU/Yr)	7.1E+04	1.4E+05	4.3E+05	8.5E+05	1.3E+06
Tails (kgU/Yr)	8.2E+05	1.6E+06	4.9E+06	9.8E+06	1.5E+07
Feed ($kg^{235}U$/Yr)	6.3E+03	1.3E+04	3.8E+04	7.6E+04	1.1E+05
Product ($kg^{235}U$/Yr)	3.5E+03	7.1E+03	2.1E+04	4.3E+04	6.4E+04
Tails ($kg^{235}U$/Yr)	2.8E+03	5.6E+03	1.7E+04	3.3E+04	5.0E+04
Feed (SQ/Yr)	84.4	168.8	506.3	1012.6	1519.0
Product (SQ/Yr)	47.2	94.5	283.4	566.9	850.3
Tails (SQ/Yr)	37.1	74.3	222.8	445.6	668.4
σ_{MUF}($kg^{235}U$)	13	26	76	152	220
σ_{MUF}(SQ)	0.17	0.35	1.0	2.0	2.9

ACCOUNTANCY VERIFICATION UNDER STANDARD HSP SAFEGUARDS

The IAEA uses a three tier set of verification methods for gross, partial, and bias defects in the random sampling plan to gain the level of detection probability for a facility and nuclear material in question.[14] The IAEA defines the number of total samples, n_s, as:

$$n_s = N_{item}(1 - \beta^{1/m}) \tag{3}$$

where:

n_s = total sample size

N_{item} = the number of items in a stratum

β = non-detection probability = $1 - P_D$

$m = M/x$

M = goal amount, kgU of ^{235}U = 75 kgU of ^{235}U for LEU

x = average nuclear material weight of an item in the stratum, kgU of ^{235}U.

The sample size, n_s, is then split between gross, partial, and bias defect measurements which is determined by weighting the size of the uncertainties in the following equation for total (relative) measurement uncertainty, δ_i:

$$\delta_i = (\delta_O^2 + \delta_I^2)^{1/2} \tag{4}$$

where:

δ_O = operator error component

δ_I = inspector error component

The IAEA calculates these numbers over the different uncertainty ranges for gross, partial, and bias defect measurements. Table 3 shows the desired ranges of the gross, partial and bias defect measurement uncertainties for operator–inspector measurement systems.[15] An international team of NDA and DA experts evaluated the various verification methods and established target values for operator and inspector measurement systems known as the International Target Values (ITVs), which state under nominal good NDA or DA practices what uncertainty values can be achieved with each technique.[16] Hence, we can calculate what the sample sizes would be for the material throughput for our five model GCEPs described in Table 2, for various safeguards approaches noted in Table 4. We note that we define three quantities for measurements in for GCEPs safeguards. There is the NDA sample measurement for ^{235}U enrichment which is a gross or partial defect measurement for GCEPs. There is the DA sample measurement for ^{235}U enrichment which is a bias defect measurement for GCEPs. Finally, there is the mass weighing of the UF_6 which by assuming a constant stoichiometric value of 0.6761 for the uranium composition of UF_6 and multiplying this value times the UF_6 weight produces the uranium mass. The mass weighing is either a partial or bias defect measure. Each measurement contents a random and a systematic uncertainty.

TABLE 3: Operator/Inspector Measurement System Recommended Error Limits

METHOD CODES	INTERPRETATION	RELATIVE ERROR RANGES	DETECTABLE DEFECT SIZE
H (Gross Defect)	Quantitative through NDA (Verification in the attribute mode using the least accurate method), or	$0.0625 < \delta_i \leq 0.125$	GROSS
	Qualitative through NDA	Error can't be assigned	GROSS
F (Partial Defect)	Quantitative through NDA (Verification in the attribute mode using a better accurate method)	$0.010 < \delta_i \leq 0.0625$	PARTIAL
E (Bias Defect)	Quantitative through NDA (Verification in the variables mode using the most accurate method) e.g.	$\delta_i \leq 0.01$	BIAS
D (Bias Defect)	Quantitative through DA (Verification in the variables mode using the most accurate method)	$\delta_i \leq 0.01$	BIAS

TABLE 4: Target Values for Advanced Safeguards Concepts at GCEPs

Measurement Uncertainties		A ATTENDED STD HSP		B UNATTENDED MSSP SPEC		C UNATTENDED NEUT DET		D UNATTENDED AEM ACC	
		Random	Systematic	Random	Systematic	Random	Systematic	Random	Systematic
NDA	Feed	10	8	8	5	2.6	5	1.5	1.5
Uncertainties	Product	4	2	4	2	2	5	1	1
	Tails	20	15	15	10	3.2	5	2	2
DA	Feed	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Uncertainties	Product	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	Tails	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Weight	Feed	0.05	0.05	15	4	1.5	6.5	0.05	0.05
Uncertainties	Product	0.05	0.05	10	2	1.5	6.5	0.05	0.05
	Tails	0.05	0.05	20	6	1.5	6.5	0.05	0.05

The first case, the standard HSP attended inspector inspection approach using the ITVs for instrument performance (Table 4 (Concept A - STD HSP) column), is the base case to compare against the advanced safeguards approaches under development. Assuming the 50% probability of detection prescribed by the IAEA for all three strata, Tables 5 through 9 show the sample sizes for the HSP safeguards approach, marked Concept A, using inspector attended monitoring systems for gross and partial defects. The IAEA uses NaI detectors for ^{235}U enrichment measurements for feed and tails, HPGe detectors for ^{235}U enrichment measurements for product, and thermal ionization mass spectrometry (TIMS) for DA. The IAEA uses authenticated operator scales or inspector load cell-based weighing systems for uranium weight. Because of the large values for tails uncertainty for NDA, the IAEA would need to take large numbers of tails DA samples and large numbers of feed samples which make the GCEP safeguards tedious and labor intensive for both inspector and operator. We can see as the plant size expands, the taking of DA becomes prohibitive with time and effort involved in taking and analyzing DA samples. The analysis of these DA samples can be an expensive and time-consuming part of GCEPs safeguards.

Since the IAEA sees the future of verification as being the use of unattended and possibly remotely monitored NDA systems even doing inspections remotely, the U.S. DOE laboratory research teams[17] are exploring some concepts as including the use of the operator's load cells and accountancy scales[18], neutron detectors for enrichment and mass[19], tracking of cylinders to ensure CofK of a specific cylinder and its contents[20], and advanced enrichment monitoring.[21] The specifications for such a system with unattended flow and monitoring capabilities are seen in Concept B – MSSP SPEC in Table 4. The specifications of Concept B come from the IAEA's Member State Support Program (MSSP) task requesting a study to investigate building a system with has the same performance as present attended NDA systems with the advantage of no inspector labor to operate the systems and a mass measurement capability that has on the order of 10–20% random error and 2–6% systematic error over all three strata.[22] The IAEA could duplicate the performance of the standard HSP safeguards in unattended mode especially assuming the withdrawal system in a large plant is spread over 4–10 production units as opposed to one huge production unit with one withdrawal system. Hence, by spreading the real time material balance across 1–9 production units having unconnected UF_6 handling stations, the unattended system would be more sensitive than if one central UF_6 handling station fed and withdrew all of the UF_6 in the plant. Hence, by spreading out the UF_6 handling across assay units of 1000 MtSWU/yr it takes longer for a single product cylinder to be filled since all of the assay units cannot fill a single cylinder. The prescribed uncertainties of the unattended mass measuring system in Concept B will be less accurate than weighing the UF_6 on the IAEA's load cells or operator accountancy scales. Hence, this higher uncertainty in mass measurement corresponds to an increased need for DA samples to get the same performance as in HSP safeguards even with similar enrichment measurement uncertainties.

However, with verification of all UF_6 material introduced into and withdrawn from the cascades combined with random inspections and design information verification, we could gain much greater confidence that no undeclared feedstock is being used and no undeclared product is being produced. The IAEA could also state that by covering the undeclared feed diversion pathway perhaps only a limited number of DA samples taken at random inspections at a random low-low level, i.e., the

IAEA's lower than random low probability of detection value of "Random Low-Low" with P_D = 10%, during the year could suffice to verify ^{235}U at the bias defect level. The remote system in Concept B giving 100% undeclared activities verification and 100% gross and partial defect verification would complement the bias defect measure and provide a reason to relax the bias defect standard. Hence, this monitoring of 100% of the cylinders is greater than the IAEA's random high detection range (P_D =90%) with 100% coverage of the cylinders for gross and partial defects and provides 100% check on undeclared feed and complementary knowledge of the enrichment and flows in the plant. This gives the IAEA confidence that fluctuations in enrichment and flow are not occurring because of undeclared feeding and withdrawing of UF_6. Concept B calculations, shown in Table 3, show that P_D =10% level of DA samples, shown in the parentheses in the DA samples rows, is only 16% of the amount needed for P_D = 50%. The IAEA could take these 24 DA samples with ease during 4–6 random inspections during the year.

We do not propose any systems for Concept B here but only calculate the sampling needs of a system with this performance. In the coming paragraphs we will describe two possible systems which, in fact, we predict could exceed the Concept specifications. Starting with the Concept B unattended system specifications and the IAEA's Operations Division B description of its needs and desires for advanced unattended GCEPs safeguards capabilities[23] we have created these two NDA systems that could be applied to a GCEP. It could be possible to have both in place to provide a means of cross-checking the data and giving assurances of the authenticity of the data or using each one independently. Concept C – NEUT DET in Table 4 uses NDA and mass measurement capabilities from passive neutron measurements.

One neutron detection system developed at LANL provides the mass of uranium in UF_6 cylinders. It uses total neutron counting, assuming a known enrichment, to give the mass in lieu of or to authenticate the load cell or accountancy scale mass at a GCEP. UF_6 produces neutrons primarily from $^{19}F(\alpha,n)^{22}Na$ reactions and ^{238}U spontaneous fission. In enriched uranium, ^{234}U is the dominant α-emitter and, hence, indirectly the principle source of neutrons in UF_6.[24] In general, the enrichment of ^{234}U follows that of ^{235}U in centrifuge enrichment processes. If the enrichment is known, then the mass of uranium can be determined from the total neutron count rate.

The detector can determine uranium mass in feed, product, and tails cylinders. The data analysis assumes a known $^{234}U/^{235}U$ ratio and ore-based feed (i.e., not from reprocessed fuel). Computational modeling studies provided an estimate of the total measurement uncertainties. The random uncertainty due to counting statistics should be less than 1%. Systematic uncertainties arise from the distribution of the UF_6 within the cylinder, calibration error, variations in the $^{234}U/^{235}U$ ratio, and background effects. The unknown source distribution creates the largest source of systematic uncertainty. The estimated total systematic uncertainty is 5-6%. For our study here we have chosen a random uncertainty of 1.5% and a systematic uncertainty of 6.5% for the weight measure for all three strata as a conservative estimate for the system.

In addition to the mass of UF_6 within a cylinder, another component of the system under development at LANL will be used for determining uranium enrichment. It uses total neutron counting to verify the load cell mass. Preliminary modeling studies show that both the doubles-to-singles ratios as well as the cadmium ratio are useful relationships for determining enrichment in UF_6 cylinders. Currently, work is focused on optimizing the design and data analysis method. Although the design is not yet finalized, the projected uncertainty estimates are 2% random and 5% systematic which are used for the enrichment uncertainty for the product stratum in this study. We took a weighting of 1.29 and 1.6 multiplied by the 2% of the product to estimating the uncertainty for the feed and tails strata, respectively. Hence, we assumed degradation in accuracy with lower enrichment than LEU so that the feed and tails have an uncertainty of 2.6% and 3.2%, respectively. We used a systematic uncertainty of 5% for the enrichment measure for all three strata as a nominal achievable goal for the system.

We envision a system that could be built onto the trolley that moves the cylinders from the storage areas to the feed/withdrawal stations or as a portal monitor system. The measurements could be made during the periods between loading feed into the heating boxes or prior to moving the product and tails to storage areas after they are moved from the cooling boxes. The load cells in the heating and cooling boxes provide a backup and authentication of the cylinder uranium weight as measured by the neutron detection system. The challenge of using the load cells is how to analyze the load cell data and how to ensure that proprietary information about feed and withdrawal operations is protected. During the December 2009 enrichment conference in Chester, United Kingdom, URENCO officials made the issue of the proprietary nature of this load cell information a possible stumbling block to the use of the load cells. At a minimum, the load cells would count cylinders being placed in the heating or cooling boxes and would show if a cylinder was empty or full. This 100% gross defect test of the cylinders and check on operator mailbox declarations would be an improvement over what is available to inspectors now for undeclared LEU production and on any mailbox scheme that depends on short notice random inspections (SNRIs). The number of SNRIs needed as plants increase in size to be statistically relevant in detecting undeclared activities at a 50% probability of detection can be large. In fact, the number of SNRIs can be so large, 30–40 SNRIs per year or more, as to be virtually indistinguishable from a resident inspector in scope of labor and travel costs for the inspectorate and intrusiveness for the operator. The system can act as the SNRI or Unannounced Inspection (UI) during a remote inspection and remove both the inspector cost and intrusiveness to the operator while providing more meaningful operational information.

The IAEA and the operators have shown a desire to build a safeguards approach around use of the operator's accountancy scales for weight measurements and an advanced enrichment monitor for ^{235}U enrichment. This is our Concept D – AEM ACC for Advanced Enrichment Monitor (AEM) and use of accountancy scales and load cells. This concept uses authenticated operator accountancy scales to get the mass of the UF_6 in the cylinders in an unattended mode and an Advanced Enrichment Monitor (AEM) at the headers feeding or withdrawing from the cascades to measure the enrichment of UF_6. Hence, this system will have the enrichment of the feed, product and tails cylinders available without having to physically measure each cylinder. We have assumed that the performance goals of this system, as shown in Table 4, will have low uncertainties in the AEM (1–2% for both random and systematic uncertainties in all three strata with the performance degrading with decreased enrichment) and the accountancy scales have the uncertainties for such a measurement system documented in the ITVs.

One of the challenges of the unattended system is to insure that a cylinder declared as being attached to the process and measured by process load cells can be authenticated to be the same cylinder declared by the operator to be measured by the neutron system or the accountancy scales. This system could benefit from a cylinder tracking system to match cylinders to the stations they entered or exited. The integrated load cell data from the autoclave or hot box can provide a backup mass value to verify the operator accountancy scale mass data if the system can be designed in such a way to protect proprietary UF_6 mass flow data. Howell, DelBeke, and others have investigated analysis of the data and how to use it to draw conclusions about the diversion of UF_6 from the plant.[25,26] Algorithms to tie the load cell data to accountancy scale data can "cross" authenticate the cylinder weights by having two independent verification methods, such as load cells and accountancy scales, check each other. Implementing Concepts C and D together would provide an independent means of nondestructively measuring both uranium mass and ^{235}U enrichment while comparing these measurements against load cell data and cylinder count in near real-time. It would be difficult for the operator to fool the neutron detector, the accountancy scales, the load cells, the neutron detector, and the AEM without producing anomalous data. Lebrun from the IAEA is a champion of this "defense in depth" "cross" authentication approach for verification.[27]

When we look at the data from the results in Tables 5 through 9 for all four safeguards concepts and for the range of the five GCEPs, we see several important patterns. Because of the lower uncertainties inherent in the detectors used in attended inspections in Concept A, the sampling plan demands a certain number of DA samples to reach the PD=50%. This number is not so prohibitive in the case of the 500 MtSWU/yr plant with 20 total DA samples to be taken, but as plant capacity increases this number becomes a concern. With plants in 3000–9000 MtSWU/yr range, which are operating and under construction today, the number of DA samples ranges from 116–345. An inspector doing monthly inspections would need to take between approximately 10–30 samples for DA at each inspection. Sampling for DA is very time consuming and intrusive to operations and at

6000–9000 MtSWU/yr plants would require significant IAEA resources. Concept B actually makes this situation worse since the IAEA specifications for mass measurement have much higher uncertainties than are seen in attended inspections. Hence, if we stick to having bias defect measurements in the unattended modes, a lot of inspection effort will still be needed just to collect the DA samples. The Concept C and D systems do reduce the number of DA samples needed. However, for Concept C this brings down the number to about 3/4 of the Concept A values for DA samples. We note that Concept D brings down the DA samples to approximately 1/6 of those required by Concept A. Hence, if the AEM concept can deliver this performance even a 9000 MtSWU/yr plant would need only 58 DA samples/yr or approximately 5 DA samples/month with 12 inspections/yr.

TABLE 5: Sampling Plans for Advanced Safeguards Systems at 500 MtSWU/yr GCEP

Feed	117	cylinders	50% PD for NDA			
Product	59	cylinders	50% PD (10% PD) for DA			
Tails	105	cylinders				
Measurements/Inspection			A	B	C	D
			ATTENDED STD HSP	UNATTENDED MSSP SPEC	UNATTENDED NEUT DET	UNATTENDED AEM ACC
NDA & Weighing	Feed		27	24	30	34
	Product		15	12	13	17
	Tails		13	12	18	21
	TOTAL		55	48	61	72
DA & Weighing	Feed		8	11(2)	5(1)	1(1)
	Product		3	6(1)	5(1)	1(1)
	Tails		9	10(2)	4(1)	1(1)
	TOTAL		20	27(5)	14(3)	3(3)
Total	Feed		35	35	35	35
	Product		18	18	18	18
	Tails		22	22	22	22
	TOTAL		75	75	75	75

TABLE 6: Sampling Plans for Advanced Safeguards Systems at 1000 MtSWU/yr GCEP

Feed	234	cylinders	50% PD for NDA		
Product	118	cylinders	50% PD (10% PD) for DA		
Tails	210	cylinders			
Measurements/Inspection		A	B	C	D
		ATTENDED STD HSP	UNATTENDED MSSP SPEC	UNATTENDED NEUT DET	UNATTENDED AEM ACC
NDA & Weighing	Feed	54	47	58	66
	Product	30	22	25	33
	Tails	26	24	37	42
	TOTAL	110	93	120	141
DA & Weighing	Feed	15	22(4)	11(2)	3(1)
	Product	5	13(2)	10(2)	2(1)
	Tails	18	20(3)	7(1)	2(1)
	TOTAL	38	55(9)	28(5)	7(3)
Total	Feed	69	69	69	69
	Product	35	35	35	35
	Tails	44	44	44	44
	TOTAL	148	148	148	148

TABLE 7: Sampling Plans for Advanced Safeguards Systems at 3000 MtSWU/yr GCEP

3000 MTSWU/yr PLANT					
Feed	702	cylinders	50% PD for NDA		
Product	354	cylinders	50% PD (10% PD) for DA		
Tails	630	cylinders			
Measurements/Inspection		A	B	C	D
		ATTENDED STD HSP	UNATTENDED MSSP SPEC	UNATTENDED NEUT DET	UNATTENDED AEM ACC
NDA & Weighing	Feed	160	140	175	198
	Product	88	66	74	99
	Tails	76	72	109	123
	TOTAL	324	278	358	420
DA & Weighing	Feed	46	66(10)	31(5)	8(2)
	Product	16	38(6)	30(5)	5(1)
	Tails	54	58(9)	21(4)	7(1)
	TOTAL	116	162(25)	82(14)	20(4)
Total	Feed	206	206	206	206
	Product	104	104	104	104
	Tails	130	130	130	130
	TOTAL	440	440	440	440

TABLE 8: Sampling Plans for Advanced Safeguards Systems at 6000 MtSWU/yr GCEP

6000 MTSWU/yr PLANT						
Feed		1404	cylinders	50% PD for NDA		
Product		708	cylinders	50% PD (10% PD) for DA		
Tails		1260	cylinders			
Measurements/Inspection			A	B	C	D
			ATTENDED STD HSP	UNATTENDED MSSP SPEC	UNATTENDED NEUT DET	UNATTENDED AEM ACC
NDA & Weighing	Feed		320	280	350	397
	Product		177	132	149	198
	Tails		153	143	219	247
	TOTAL		650	555	718	842
DA & Weighing	Feed		92	132(20)	62(10)	15(3)
	Product		31	76(12)	59(9)	10(2)
	Tails		107	117(18)	41(7)	13(2)
	TOTAL		230	325(50)	162(26)	38(7)
Total	Feed		412	412	412	412
	Product		208	208	208	208
	Tails		260	260	260	260
	TOTAL		880	880	880	880

TABLE 9: Sampling Plans for Advanced Safeguards Systems at 9000 MtSWU/yr GCEP

9000 MTSWU/yr PLANT						
Feed		2106	cylinders	50% PD for NDA		
Product		1062	cylinders	50% PD (10% PD) for DA		
Tails		1890	cylinders			
Measurements/Inspection			A	B	C	D
			ATTENDED STD HSP	UNATTENDED MSSP SPEC	UNATTENDED NEUT DET	UNATTENDED AEM ACC
NDA & Weighing	Feed		479	419	523	594
	Product		265	198	223	297
	Tails		230	215	329	370
	TOTAL		974	832	1075	1261
DA & Weighing	Feed		138	198(31)	94(15)	23(4)
	Product		47	114(18)	89(14)	15(3)
	Tails		160	175(27)	61(10)	20(3)
	TOTAL		345	487(76)	244(39)	58(10)
Total	Feed		617	617	617	617
	Product		312	312	312	312
	Tails		390	390	390	390

One of the aims of the advanced safeguards approaches is for the IAEA to be able to depend on the remote unattended systems to replace the labor of the inspectors and to reduce both the length and frequency of inspections at GCEPs. We noted that Concept C could reduce the need for DA samples by around a third and Concept D could reduce the need for DA samples substantially by around 5/6th. We stated above that the 100% coverage of all strata with gross and partial defect tests with the attended system gives us confidence that the operator cannot introduce undeclared feedstock or remove undeclared product LEU. Hence, we could make a case for relaxing the bias defect sampling requirement from PD=50% to PD=10% for Concepts B, C, and D as shown in Tables 5-9. Tables 7-9 show that this relaxation in probability of detection for bias defects results in Concept C and D DA samples for GCEPs with capacities of 3000-9000 MtSWU/yr plummeting from a range of 116-345 total DA samples in all three strata with PD=50% in the Concept A attended mode to 25-39 DA samples with PD=10% in all three strata in Concept C and 4-10 DA samples with PD=10% in all three strata with Concept D. Hence, we can propose with the bias defect test having PD=10% that the IAEA could do 4-6 UI on a random basis each year. During each inspection the inspectors would check the remote systems for tampering, do spot weighing of 1-6 selected cylinders, and take only DA samples from those same cylinders. The actual sample number, i.e., 1-6, would depend on the plant throughput and system performance as seen in the calculations. However, even taking the maximum 6 DA samples and spot check weighing during 4-6 inspections is not an onerous load over an inspection lasting two-three days with 2-3 inspectors. We note that inspector will need to do more work if they find the unattended system is not functioning nominally. More research is needed to develop a strategy to recover from a system malfunction or operator tampering between inspections.

With further respect to the DA samples, if the IAEA could use an on-site DA method, it would improve timeliness and reduce the chance of the loss of CofK. Since present GCEPs safeguards require the storage of DA samples on site for the entire material balance period, the risk of loss of CoK of the whole DA sample batch is credible if the seals on the storage cabinet are accidently broken or deliberately compromised. Furthermore, it can take months for the samples to be shipped and analyzed making it difficult to have timely conclusions for the material balance period. Hence, a technique for on-site DA of samples with comparable low uncertainties as can be obtained with TIMS or gas source mass spectrometry (GSMS) would be desirable for development for the IAEA to use at a GCEP. The IAEA is pursuing such a strategy with the development of an instrument based on Tunable Diode Laser Spectrometry.[28] Furthermore, an NDA technique with uncertainties less than or equal to 1% that could be used as a bias defect tool, as described as Method E in Table 3, would also be desirable because it would be easier than taking DA samples and analyzing the samples. If the AEM performs as hoped it may be able to provide performance comparable to Method E. However, an intermediate option may be a NDA technique that could be used on the sample bottles on-site and during an inspection. If we pursue the course of taking bias defect DA samples at the 10% probability of detection level with an immediate on-site Method E measurement of the sample bottle, the sample taking and NDA measurement could be done during a few unannounced inspections during the year. The unannounced inspections would provide a check if the unattended systems are functioning nominally and if the operator did not tamper with them and the on-site DA of samples would avoid the sample custody issue that could lead to loss of CofK of an entire year's DA sample base.

CONCLUSION

The analysis in this paper shows that the current safeguards approaches used by the IAEA at large GCEPs can be enhanced in order to provide better detection capabilities of both declared and undeclared LEU production using unattended NDA techniques. As shown in the examples of Concepts B, C, and D, the use of an unattended system that could give an overview of the entire process, complementary data on the enrichment process, and accurate measurements of enrichment and weights of the UF_6 feedstock, tails, and product is a major step in enhancing the ability of NDA beyond present attended systems. This possibility of monitoring the feed, tails, and product header pipes in such a way as to gain safeguards relevant flow and enrichment information without compromising the intellectual property of the operator would be a huge step forward in being able to monitor undeclared production. This paper shows how developments in process monitoring can progressively make IAEA safeguards inspections activities more effective by the use of unattended systems and more efficient by reducing both inspector and operator time and labor by reducing the need for and numbers of DA samples. The use of mass and enrichment monitoring by unattended systems can provide valuable process monitoring and accountancy data as well as the ability to verify with the advanced enrichment monitors if undeclared HEU is being produced. The use of the operator's accountancy scales and load cells combined with the AEM will probably provide the most accurate system for measuring both the uranium mass and ^{235}U enrichment. However, passive neutron systems show promise for making independent measurements that could complement the other measures. Having independent measures can help cross check the data and cross authenticate the declarations of the operator and the data. The systems and technologies in this paper need to be pursued through research and development to provide instruments with the goal capabilities of low uncertainty and robustness that will give the IAEA enhanced safeguards at GCEPs.

REFERENCES

[1] J. H. Menzel, "Safeguards Approach for Gas Centrifuge Type Enrichment Plants", authored by the Hexapartite Safeguards Project (HSP), Journal of the Institute of Nuclear Materials Management, Vol. 12, Number 4/Winter 1983.

[2] M.D. Rosenthal, Personal Communication, Brookhaven National Laboratory, Upton, NY, June 17, 2009.

[3] J.W. Tape, "Customizing Safeguards: State-Level Factors," Proceedings Fifth Joint INMM/ESARDA Workshop, Santa Fe, NM, November 2005.

[4] B.D. Boyer and M.T. Swinhoe, "Defining the Needs for Non Destructive Assay of UF_6 Feed, Product, and Tails at Gas Centrifuge Enrichment Plants and Possible Next Steps," Proceedings INMM 50th Annual Meeting, Tucson, AZ, July 2009.

[5] I. Tsvetkov, W. Bush, R. Fagerholm, D. Hurt, M. Jordan, and J. Leicman, "Implementation of the IAEA's Model Safeguards Approach for Gas Centrifuge Enrichment Plants," 29th ESARDA Annual Meeting, Aix en Provence, France, May 22–24, 2007.

[6] P.J. Friend, T. Korbmacher, J. Dackner, and M. Jordan, "Field Trial of Mailbox Concept at a URENCO Enrichment Plant," Proceedings INMM 49th Annual Meeting, Nashville, TN, July 2008.

[7] A.L. Aronson and D.M. Gordon, *The "Mailbox" Computer System for the IAEA Verification Experiment on HEU Downblending at the Portsmouth Gaseous Diffusion Plant*, Brookhaven National Laboratory, Report BNL-52605/ISPO-411, 31 July 2000.

[8] "IAEA Verification Experiment at the Portsmouth Gaseous Diffusion Plant", D.M. Gordon, M. Subudhi, O.L. Calvert, T.N. Bonner, J.G. Adams, R.C. Cherry, and N.E. Whiting, Proceedings INMM 39th Annual Meeting, Naples, Florida, 26-30 July 1998.

[9] N. Whiting, "Conceptual Approach for Applying Safeguards at a large Gaseous Centrifuge Enrichment Plant," Proceedings 2nd JAEA-IAEA Workshop on Advance Safeguards Technology for the Future Nuclear Fuel Cycle, Tokai-mura Ibaraki, Japan, November 2009.

[10] M. Laughter, "Using Unattended Monitoring to Trigger Inspections," Proceedings 2nd JAEA-IAEA Workshop on Advance Safeguards Technology for the Future Nuclear Fuel Cycle, Tokai-mura Ibaraki, Japan, November 2009.

[11] M. Zendel and N. Khlebnikov, "Optimizing and Joining Future Safeguards Efforts by 'Remote Inspection'," Proceedings 2nd JAEA-IAEA Workshop on Advance Safeguards Technology for the Future Nuclear Fuel Cycle, Tokai-mura Ibaraki, Japan, November 2009.

[12] *IAEA Safeguards Glossary*, 2001 edition, International Atomic Energy Agency, Vienna, Austria, 2002.

[13] *IAEA Safeguards Glossary*, 2001 edition, International Atomic Energy Agency, Vienna, Austria, 2002, p. 53.

[14] J.L. Jaech and M. Russell, *Algorithms to Calculate Sample Sizes for Inspection Sampling Plans, "Nuclear Safeguards* International Atomic Energy Agency Report STR-261 (Rev. 1), Vienna, Austria, March 1991.

[15] B. Boyer, *White Paper On The Goals For Safeguarding Gas Centrifuge Enrichment Plants,* LA-UR-08-4905, Los Alamos National Laboratory, Los Alamos, NM, August 2008.

[16] H. Aigner, et al., *International Target Values 2000 for Measurement Uncertainties in Safeguarding Nuclear Materials*, International Atomic Energy Agency Report STR-327, Vienna, Austria, April 2001.

[17] P.C. Durst, "An Analysis of Advanced Safeguards Approaches for New Large-Scale Uranium Enrichment Plants," Proceedings INMM 49th Annual Meeting, Nashville, TN, July 2008.

[18] A.M. Krichinsky, J.W. Hickerson, M.D. Laughter, C.A. Pickett, G.D. Richardson, N.C. Rowe, J.M.Whitaker, W.A. Wutzler, J.R. Younkin, "Evaluating Continuous Load-Cell Monitoring as an

Effective Safeguards Strategy for Feed And Withdrawal Systems," Proceedings INMM 49th Annual Meeting, Nashville, TN, July 2008.

[19] K.A. Miller, H.O. Menlove and M.T. Swinhoe, "Neutron-Based Enrichment Meter for UF_6 Cylinders," LA-UR 09-05036, Los Alamos National Laboratory (2009).

[20] C.A. Pickett, D.N. Kovacic, J. M. Whitaker, J.R. Younkin, J. Hines, M.D. Laughter, J. Morgan, B. Carrick, K. Whittle, B. Boyer, "Results from a 'Proof-of-Concept' Demonstration of RF-Based Tracking of UF_6 Cylinders during a Processing Operation at a Uranium Enrichment Plant," Proceedings INMM 49th Annual Meeting, Nashville, TN, July 2008.

[21] K.D. Ianakiev, B.S. Alexandrov, B.D. Boyer, T.R. Hill, D.W. MacArthur, T. Marks, C.E. Moss, G.A. Sheppard, and M.T. Swinhoe, "New Generation Enrichment Monitoring Technology for Gas Centrifuge Enrichment Plants," Proceedings INMM 49th Annual Meeting, Nashville, TN, July 2008.

[22] B. Boyer, M. Swinhoe, K. Miller, B. McGinnis, J. M. Whitaker, M.D. Laughter, A. Solodov, J. Tanner, E. Smith, J. Benz, "State of the Art NDA Methods Applicable to UF_6 Cylinders," Phase I Report, SG-EQ-NDA-UR-0001, LA-UR-09-07356, Los Alamos National Laboratory, Los Alamos, NM, December 2009.

[23] N. Whiting, "Conceptual Approach for Applying Safeguards at a large Gaseous Centrifuge Enrichment Plant," Proceedings 2nd JAEA-IAEA Workshop on Advance Safeguards Technology for the Future Nuclear Fuel Cycle, Tokai-mura Ibaraki, Japan, November 2009.

[24] D. Reilly, N. Ensslin, H. Smith and S. Kreiner, *Passive Nondestructive Assay of Nuclear Materials*, pp. 435-455, NUREG/CR-5550, Office of Nuclear Regulatory Research (1991).

[25] Delbeke, J.F.A. and Howell, J. and Eklund, G. and Peerani, P. and Janssens, W., "The real time mass evaluation system as a tool for detection of undeclared cascade operation at GCEPs," Proceedings of the. 8th International Conference on Facility Operations-Safeguards Interface, , Portland, OR, April 2008.

[26] C. Cleary and R. Carchon., "Safeguards Analysis of Material Flows in a Gas Centrifuge Enrichment Plant," ESARDA Bulletin, Number 41, Ispra, Italy, June 2009.

[27] A. Lebrun, "The Role of Instrumentation in Enhancing Safeguards Verifications at Enrichment Plants," Proceedings URENCO Safeguards Conference 2009, Chester, UK, December 2009.

[28] A. Lebrun, V. Ryzhikov, M. Zendel, A. Nadezhdinskii, G. Grigorev, and L. Mechold, "A Tunable Diode Laser Spectroscopy (TDLS) System for on site UF6 analytical enrichment measurements," Proceedings INMM 49th Annual Meeting, Nashville, TN, July 2008.