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DEFINING THE NEEDS FOR NON DESTRUCTIVE ASSAY OF UF_6 FEED, PRODUCT, AND TAILS AT GAS CENTRIFUGE ENRICHMENT PLANTS AND POSSIBLE NEXT STEPS

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ABSTRACT

Current safeguards approaches used by the IAEA at gas centrifuge enrichment plants (GCEPs) need enhancement in order to detect undeclared LEU production with adequate detection probability using non destructive 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 UF_6 bulk material used in the process of enrichment at GCEPS. The inspectors also take destructive assay (DA) samples for analysis off-site which provide accurate, on the order of 0.1% to 0.5% uncertainty, data on the enrichment of the UF_6 feed, tails, and product. However, DA sample taking is a much more labor intensive 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 the results and contains the possibility of the loss of the continuity of knowledge of the samples during the storage and transit of the material. Use of the IAEA's inspection sampling algorithm shows that while total sample size is fixed by the total population of potential samples and its intrinsic qualities, the split of the samples into NDA or DA samples is determined by the uncertainties in the NDA measurements. Therefore, the larger the uncertainties in the NDA methods, more of the sample taken must be DA samples. Since the DA sampling is arduous and costly, improvements in NDA methods would reduce the number of DA samples needed. Furthermore, if methods of on-site analysis of the samples could be developed that have uncertainties in the 1-2% range, a lot of the problems inherent in DA sampling could be removed. The use of an unattended system that could give an overview of the entire process giving complementary data on the enrichment process as well as accurate measures of enrichment and weights of the UF_6 feed, tails, and product would be a major step in enhancing the ability of NDA beyond present attended systems. The 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 including proprietary equipment and operational parameters would be a huge step forward. This paper contains an analysis of possible improvements in unattended and attended NDA systems including such process monitoring and possible on-site analysis of DA samples that could reduce the uncertainty of the inspector measurements reducing the difference between the operator's and inspector's measurements providing more effective and efficient IAEA GCEPs safeguards.

INTRODUCTION

The International Atomic Energy Agency (IAEA) currently safeguards large low-enriched uranium (LEU, with <20% enriched ^{235}U) gas centrifuge enrichment plants (GCEPs) in several countries. In 2009 the IAEA uses the same basic approach to safeguard GCEPs that the Hexapartite Safeguards Project (HSP) recommended in 1983 with some enhancements[1,2]. LEU GCEPS safeguards have three principal safeguards concerns for nuclear material diversions which are:

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

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

3. Production 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 the 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 required to enrich 3.5% ^{235}U to 90% ^{235}U is about one-third of that required to enrich natural uranium to 90% ^{235}U. Thus, a clandestine cascade, as described above, designed to produce HEU from LEU is smaller and more easily concealed than a full-scale cascade to produce HEU from natural uranium. The HSP safeguards approach explicitly addressed the first two diversion concerns but did not address the third concern which centers on "undeclared feed." In this scenario, the operator would introduce undeclared feed UF_6 that was not inspected by the IAEA secretly into the 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 and undeclared product and depleted tails by falsifying the books and insuring any discrepancies in enrichment values or material amounts would be undetectable by IAEA safeguards.

The IAEA moved in recent years to cover this gap in the GCEPs safeguards approach by rolling out a new model safeguards approach which proposed randomized inspections and the use of the "Mailbox" concept to allow the IAEA to detect undeclared operations[3]. There was a trial at the URENCO Gronau, Germany GCEPs plant to examine the feasibility of this approach[4]. The field trial successfully demonstrated the concept as had earlier trials at the Portsmouth Gaseous Diffusion Plant in the 1990's to verify HEU blenddown[5,6].

OPERATOR'S DIVERSION SCENARIOS AND INSPECTION NEEDS

The IAEA also has an interest in improving the quality of the nondestructive assay (NDA) and destructive assay (DA) measurements done at GCEPs. An operator can divert material by having the measurement uncertainties of the operator be large enough that over the course of the material balance period of one-year that the Material Unaccounted For (MUF) is big enough compared to the throughput of the GCEP that a Significant Quantity (SQ) can be literally lost in the noise of measurement uncertainties[7]. This diversion strategy is known as **diversion into MUF** and the operator can remove all or partial amounts of UF_6 from a few cylinders to get an SQ of enriched material and falsify the records. The second strategy for an operator to divert material is to remove the material but not to falsify the records but depend on the uncertainties of the inspector's measurements to not be able to reveal the discrepancy. This is known as **diversion into D** (the overall operator-inspector difference statistic) where operator-inspector difference, d_i, is defined as:

$$d_i = [O_i - I_i]/ O_i \qquad (1)$$

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:

$$MUF = PB + X - Y - PE \qquad (2)$$

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 uranium element and ^{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 an operator's instruments at a GCEP are accurate to 1 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[8]. For example, in an enrichment plant of 3000 MTSWU/yr, which is typical of the large new GCEP facilities coming on line world-wide either as new construction or older plant expansion, the amount of material that one δ_E would represent is ~1 SQ of feed, ~0.7 SQ of enriched product, and ~0.4 SQ of depleted tails. Hence, $3\sigma_{MUF}$ would then be ~3 SQ of feed, ~1.9 SQ of enriched product, and ~1.3 SQ of depleted tails. So over the course of a year a $3\sigma_{MUF}$ alarm level would allow for the hiding of more than an SQ diversion of feed, tails or most importantly LEU product from the GCEP. The σ_D value involves applying measurement error estimates, from both the operator and inspector, to measured strata (feed, product and tails, as stated above, in GCEPs) and summing the stratum variances. A MUF > $3\sigma_{MUF}$ or D < $3\sigma_D$ indicates diversion. Hence, the ability of the IAEA accountancy verification to be robust depends on both operator and inspector differences to be small. As shown here, even the accurate measurements of the operator can still allow material to be lost in the MUF if a GCEP is large enough. With today's larger plants, the basic accountancy verification techniques will need to be improved and revised to get the robustness in safeguards measures needed to properly safeguard a GCEP.

ACCOUNTANCY VERIFICATION UNDER STANDARD HSP SAFEGUARDS

The IAEA uses at 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[9]. The IAEA defines the number of total samples, n_s, as:

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

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 measurement which is determined weighting the size of the uncertainties in the following equation for total (relative) measurement uncertainty, δ_i:

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

where:

δ_O = operator error component

δ_I = inspector error component

The IAEA calculate these numbers over the different uncertainty ranges for gross, partial and bias defect measurements. Table 1 below shows the ranges of the gross, partial and bias defect measurements for operator/ inspector measurement systems[10]. An international NDA and DA expert team evaluated the various verification methods and have established target values for operator and inspector measurement systems known as the International Target Values (ITVs) which state under nominal good NDA or DA practice what uncertainty values can be reached[11]. Hence, we can calculate what the sample sizes would be for the material throughput for the 3000 MTSWU GCEP briefly described above using the ITVs. Tables 2 and 3 show the sample sizes for the standard HSP safeguards (STD HSP) approach, marked Option A, using inspector attended monitoring systems for gross and partial defects. The IAEA uses nominally NaI detectors for ^{235}U enrichment measurements for feed and tails and HPGe detectors for ^{235}U enrichment measurements for product. The IAEA uses authenticated operator scales or inspector load-cell based weighing systems for uranium weight. Thermal Ionization Mass Spectrometry (TIMS) functions for DA for all three strata for a $P_D = 50\%$. Because of the large values for tails uncertainty for NDA, the IAEA would need to take large numbers of tails DA samples (50% of the total tails samples) and large numbers of feed samples which make the GCEP safeguards tedious and labor intensive for both inspector and operator.

The IAEA sees the future of verification as being the use of unattended and possibly remotely accessible NDA systems. The specifications for such a system with a FEMO (Flow and Enrichment Monitor) [12,13] are seen in Option B in Tables 2 and 3. Option B has the same performance as present attended NDA systems with the advantage of no inspector labor to operate the systems and a mass flowmeter that has on the order of 10-20% random error and 2-6% systematic error over all three strata. The IAEA could duplicate the performance of the standard HSP safeguards with a few caveats. Since the flowmeter will be less accurate than weighing the UF_6, this higher uncertainty in mass measurement corresponds to an increased need for DA samples to get the same performance as in HSP safeguards. However, with verification of all UF_6 material introduced into the cascades and withdrawn from the cascades combined with random inspections of the cascade halls using

LFUA methodology, of the process feed and withdrawal stations, and Design Information Verification of the plant design and layout, we could gain much greater confidence that no undeclared feed is being used and no undeclared product being produced. Hence, the use of the concept of unified uranium could have some feasibility which it does not with the possibility of undeclared feed. With unified uranium concept[14], the IAEA only worries about the uranium mass and not the ^{235}U mass in the plant since it has covered the undeclared feed route by monitoring the ^{235}U content of the UF_6 cylinders and providing complementary measures to accountancy by having process monitoring "see" all material move into and out of the process. 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 ($P_D = 10\%$) during the year could suffice to verify ^{235}U at the bias defect level. Table 3, Option B, shows that 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.

Moving to a higher performance FEMO concept that is under development at Oak Ridge National Laboratory and Los Alamos National Laboratory, as shown Option C, having improved NDA and flowmeter capabilities could provide the same performance as Option B with a $P_D = 50\%$ without resorting to unified uranium concept described above and taking only 38 DA samples in 4-6 random inspections during the year. If the IAEA would again use the unified uranium concept, as described above in Option B, Table 3 shows that level of DA samples, shown in the parentheses in the DA samples rows, is now down to 10 DA samples.

Furthermore, if the IAEA would move to a system, shown in Option D, that can use authenticated operator accountancy scales to get the mass of the UF_6 in the cylinders combined with the Advanced Enrichment Monitor (AEM) developed for the FEMO concept to measure the enrichment of UF_6 material as it fills or drains from the cylinders, the accuracy of the unattended system could be further increased. This system could benefit from a cylinder tracking system to match cylinders to the autoclave or hot box they entered or exited from and integrated load cell data from the autoclave or hot box to provide a backup mass value to verify the operator accountancy scale mass data[15,16]. With the decreased uncertainty and increased accuracy of the Option D concept, only 15 DA samples taken at 4-6 random inspections during the year could provide the same performance as in standard HSP safeguards with 15% of the DA samples. Furthermore, if the IAEA would apply the unified uranium concept, as described in Options B and C, the number of DA samples would drop for $P_D = 10\%$ to one apiece in each stratum. The IAEA could also then assume the integrated operator scale, load cells, AEM, and cylinder tracking system should provide better undeclared feed detection than in the other three options.

With respect to the DA samples, if the IAEA could use an on-site method to analyze the DA samples, it would improve timeliness and reduce the chance of the loss of continuity of knowledge (CofK). Since present GCEP safeguards require the storing on site of the DA samples for the entire material balance period, the risk of loss of CofK of the whole DA sample batch is real if the seals on the storage cabinet are accidently broken or deliberately tampered. 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 for depleted, natural and low enriched uranium (DNLEU). Hence, a technique for on-site analysis of DA 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. Furthermore, a NDA technique with uncertainties ≤1% that could be used as a bias defect tool, as describe as Method E in Table 1, would also be desirable because it would be easier than taking DA samples and analyzing the DA samples with any tool.

CONCLUSION

The analysis in this paper shows that the current safeguards approaches used by the IAEA at gas centrifuge enrichment plants (GCEPs) need enhancement in order to detect undeclared LEU production with adequate detection probability using non destructive assay (NDA) techniques. As shown in the examples of Options B, C, and D, the use of an unattended system that could give an overview of the entire process giving complementary data on the enrichment process as well as accurate measures of enrichment and weights of the UF_6 feed, 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 including proprietary equipment and operational parameters would be a huge step forward in closing the gap of being able to monitor undeclared feed. 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. The use of a FEMO 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 the ability to authenticate cylinder movement combined with and Advanced Enrichment Monitor will probably provide the most accurate system for measuring both the uranium mass and ^{235}U enrichment. These ideas 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 GCEP safeguards.

TABLE 1: 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 (e.g. Cerenkov, bundle counter)	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. K-edge densitometer	$\delta_i \leq 0.01$	BIAS
D (Bias Defect)	Quantitative through DA (Verification in the variables mode using the most accurate method)	$\delta_i \leq 0.01$	BIAS

TABLE 2: ITV values and target values for advanced safeguards instruments

Measurements/ Inspection		A		B		C		D	
		STD HSP	STD HSP	FEMO/ ITV GRADE	FEMO/ ITV GRADE	FEMO/ LOW UNC	FEMO/ LOW UNC	AEM/OP. SCALE	AEM/OP. SCALE
		Random	Systemic	Random	Systemic	Random	Systemic	Random	Systemic
NDA	Feed	8	5	8	5	1.5	1.5	1.5	1.5
UNC	Product	4	2	4	2	1	1	1	1
	Tails	15	10	15	10	2	2	2	2
DA	Feed	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
UNC	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	4	2	0.05	0.05
	Product	0.05	0.05	10	2	4	2	0.05	0.05
	Tails	0.05	0.05	20	6	4	2	0.05	0.05

TABLE 3: Sampling Plans for HSP safeguards and advanced safeguards systems.

Measurements/Inspection Feed = 690 cylinders Product = 354 cylinders Tails = 626 cylinders TOTAL = 1670 cylinders		A STD HSP	B FEMO/ ITV GRADE	C FEMO/ LOW UNC	D AEM/OP. SCALE
NDA & Weighing	Feed	158	139	188	198
	Product	89	70	90	98
	Tails	50	44	90	95
	TOTAL	**297**	**253**	**368**	**391**
DA & Weighing	Feed	45	64(10)	15(3)	5(1)
	Product	14	33(5)	13(2)	5(1)
	Tails	50	56(9)	10(2)	5(1)
	TOTAL	**109**	**153 (24)**	**38(10)**	**15(3)**
Total	Feed	203	203	203	203
	Product	103	103	103	103
	Tails	100	100	100	100
	TOTAL	**406**	**406**	**406**	**406**

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