LA-UR- 10-03815

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Intended for: 51st Annual INMM Meeting

July 11-15, 2010
Baltimore MD
(PAPER)

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NATIONAL LABORATORY
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ANALYSIS OF THE EFFECTIVENESS OF GAS CENTRIFUGE ENRICHMENT PLANTS ADVANCED SAFEGUARDS

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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 uranium (LEU) production, detect undeclared LEU production and detect highly enriched uranium (HEU) 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 declared UF_6 containers used in the process of enrichment at GCEPs. This paper contains an analysis of possible improvements in unattended and attended NDA systems including process monitoring and possible on-site destructive assay (DA) of samples that could reduce the uncertainty of the inspector's measurements. These improvements could reduce the difference between the operator's and inspector's measurements providing more effective and efficient IAEA GCEPs safeguards. We also explore how a few advanced safeguards systems could be assembled for unattended operation. The analysis will focus on how unannounced inspections (UIs), and the concept of information-driven inspections (IDS) can affect probability of detection of the diversion of nuclear materials when coupled to new GCEPs safeguards regimes augmented with unattended systems.

INTRODUCTION

The IAEA 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. There are also several new GCEPs being built in France and the United States as well as continual expansion of the URENCO plants in Europe as well as some nuances to the HSP approach in Japan. It may be argued that the IAEA's application of HSP safeguards at these new facilities, some 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 effective and efficient deployment in any State.

Three principal safeguards concerns for nuclear material diversions from LEU GCEPs include production and diversion of a significant quantity of uranium with enrichment greater than declared (in particular, HEU with $\geq 20\%$ ^{235}U), diversion of a significant quantity of declared uranium (particularly in the form of LEU product), and 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, both of which are a major concern of the IAEA. Second, natural uranium or LEU can be used to fuel a reactor for the production of plutonium. 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 separate 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 LEU operations.[5]

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,[6] 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 UIs, Additional Protocol (AP) complementary access (CA) activities, and the application of new and novel technologies. The IAEA's Strengthened Safeguards System of the 1990s is the foundation of these advanced safeguards measures which can be seen as IDS when open source information, AP CA activity results, inspection data, and unattended system transmitted data coalesce at IAEA headquarters to drive safeguards approaches and inform inspection schedules.

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 (MBP) is big enough, compared to the throughput of the GCEP, to hide diversion of a significant quantity (SQ) in the noise of measurement uncertainties.[7] 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.** 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:

$$MUF = PB + X - Y - PE \quad (1)$$

where PB represents the physical inventory at the beginning of the period, X represents the sum of the nuclear material increases into the material balance area (MBA) during the MBP, Y represents the sum of the nuclear material decreases of the MBA during the MBP, and PE represents physical inventory at the end of the period, measured during the Physical Inventory Taking.

The MUFs are calculated for both elemental uranium and the ^{235}U isotope. 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.[8] 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. Table 1 includes yearly material flows and cylinder throughputs for five case study GCEPs that represent a range of existing or planned plant capacities. This table illustrates that as plant capacity increases, the values of σ_{MUF} and the possibility for diversion of a SQ into MUF correspondingly increase. The advanced safeguards concepts that we are exploring will not affect σ_{MUF}, but have the potential to substantially reduce the likelihood of both diversion scenarios across the range of plant capacities.

TABLE 1: 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)	115	230	690	1380	2070
Product (Cylinders/Yr)	53	106	318	636	954
Tails (Cylinders/Yr)	106	212	636	1272	1908
Feed (kgU/Yr)	9.2E+05	1.8E+06	5.5E+06	1.1E+07	1.7E+07
Product (kgU/Yr)	7.4E+04	1.5E+05	4.4E+05	8.8E+05	1.3E+06
Tails (kgU/Yr)	8.5E+05	1.7E+06	5.1E+06	1.0E+07	1.5E+07
Feed (kg ^{235}U/Yr)	6.6E+03	1.3E+04	3.9E+04	7.9E+04	1.2E+05
Product (kg ^{235}U/Yr)	3.7E+03	7.4E+03	2.2E+04	4.4E+04	6.6E+04
Tails (kg ^{235}U/Yr)	2.9E+03	5.8E+03	1.7E+04	3.5E+04	5.2E+04
Feed (SQ/Yr)	87.5	175.1	525.3	1050.6	1575.8
Product (SQ/Yr)	49	98	294.1	588.2	882.3
Tails (SQ/Yr)	38.5	77.1	231.2	462.4	693.6
σ_{MUF}(kg ^{235}U)	13	26	79	158	236
σ_{MUF}(SQ)	0.18	0.35	1.1	2.1	3.2

ACCOUNTANCY VERIFICATION UNDER STANDARD HSP SAFEGUARDS

It may be argued that the true test of an advanced safeguards concept is its ability to provide the required probability of detection (P_D) while simultaneously reducing inspection effort. In order to evaluate the effectiveness of advanced safeguards concepts, one must consider the methodology used by the IAEA in generating a random sampling plan for an inspection, the uncertainties associated with the measurements that the IAEA routinely performs, and the effort required to complete the standard IAEA HSP inspector-attended inspection.

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.[9] 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:

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

with δ_O and δ_I representing the operator and inspector error components, respectively.

The IAEA calculates these numbers over the different uncertainty ranges for gross, partial, and bias defect measurements. The IAEA assumes that the operator will provide measurements with comparable or lower uncertainties than the International Target Values (ITVs)[10], which represent nominal uncertainties achievable with each NDA and DA method for various material compositions and forms. In the standard IAEA HSP inspection at a GCEP, the inspector performs enrichment measurements of cylinders from all three strata using NaI or HPGe detectors (gross and partial defect measurements), takes samples for off-site enrichment measurements using thermal ionization mass spectrometry (bias defect measurements), and uses authenticated operator scales or inspector load cell-based weighing systems for determining uranium weight (part of a partial or bias measurement). The random and systematic uncertainties associated with these methods are listed in Table 2. Note that Table 2 also includes the uncertainties associated with three advanced safeguards concepts.

Using the IAEA's methodology[9], one can calculate the total numbers of measurements that must be performed annually by inspectors for a required P_D. One can also calculate the total numbers of measurements required for each stratum, and the numbers of gross, partial, and bias defect measurements that comprise the totals. One can then extend the methodology to other safeguards approaches—such as our three advanced unattended systems—and evaluate the potential efficiencies gained from their implementation.

TABLE 2: GCEPs Advanced Safeguards Concepts Target Values (% Rel. Std. Uncertainty)

Measurement Uncertainties		A		B		C		D	
		ATTENDED STD HSP		UNATTENDED MSSP SPEC		UNATTENDED NEUT DET		UNATTENDED AEM ACC	
		Random	Systematic	Random	Systematic	Random	Systematic	Random	Systematic
NDA Uncertainties	Feed	10	8	8	5	2.6	5	1.5	1.5
	Product	4	2	4	2	2	5	1	1
	Tails	20	15	15	10	3.2	5	2	2
DA Uncertainties	Feed	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
	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 Uncertainties	Feed	0.05	0.05	15	4	1.5	6.5	0.05	0.05
	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 analyzed, the standard HSP inspector-attended inspection approach using the ITVs for instrument performance (Table 2 (Concept A - STD HSP) column), is the base case to compare against the advanced safeguards approaches under development. Assuming a probability of detection of 50% (P_D=50%), a value deemed random medium by the IAEA, for all three strata, Table 3 shows the sample sizes for the Concept A safeguards approach using inspector-attended monitoring systems for gross and partial defects. 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 that as the plant size increases, DA becomes prohibitive with the time and effort involved in taking and analyzing the samples. The analysis of these samples can be an expensive and time-consuming part of GCEPs safeguards. Hence, one of the goals of the three proposed unattended systems B through D is to reduce the need for DA samples.

TABLE 3: Sampling Plans for Advanced Safeguards Systems at P_D=50%

P_D=50%		Measurements/Inspection																			
		A - ATTENDED STD HSP					B - UNATTENDED MSSP SPEC					C - UNATTENDED NEUT DET					D -UNATTENDED AEM ACC				
Type of Sample Measurements		500 MTSWU/yr	1000 MTSWU/yr	3000 MTSWU/yr	6000 MTSWU/yr	9000 MTSWU/yr	500 MTSWU/yr	1000 MTSWU/yr	3000 MTSWU/yr	6000 MTSWU/yr	9000 MTSWU/yr	500 MTSWU/yr	1000 MTSWU/yr	3000 MTSWU/yr	6000 MTSWU/yr	9000 MTSWU/yr	500 MTSWU/yr	1000 MTSWU/yr	3000 MTSWU/yr	6000 MTSWU/yr	9000 MTSWU/yr
NDA & Weighing	Feed	26	52	155	309	464	22	45	134	268	402	22	57	171	340	510	33	65	195	389	584
	Product	14	27	80	159	238	10	21	60	119	178	10	23	67	134	200	15	30	89	178	266
	Tails	12	25	75	149	223	12	23	70	139	208	12	37	110	219	329	21	42	125	249	373
	TOTAL	52	104	310	617	925	44	89	264	526	788	44	117	348	693	1039	69	137	409	816	1223
DA & Weighing	Feed	8	16	48	96	143	12(2)	23(4)	69(11)	137(21)	205(32)	6(1)	11(2)	32(5)	65(10)	97(15)	1(1)	3(1)	8(2)	16(3)	23(4)
	Product	2	5	14	28	42	6(1)	11(2)	34(6)	68(11)	102(16)	5(1)	9(2)	27(4)	53(8)	80(13)	1(1)	2(1)	5(1)	9(2)	14(3)
	Tails	10	19	57	114	171	10(2)	21(4)	62(10)	124(19)	186(29)	4(1)	7(2)	22(4)	44(7)	65(10)	1(1)	2(1)	7(2)	14(3)	21(4)
	TOTAL	20	40	119	238	356	28(5)	55(10)	165(27)	329(51)	493(77)	15(3)	27(6)	81(13)	162(25)	242(38)	3(3)	7(3)	20(5)	39(8)	58(11)
Total	Feed	34	68	203	405	607	34	68	203	405	607	34	68	203	405	607	34	68	203	405	607
	Product	16	32	94	187	280	16	32	94	187	280	16	32	94	187	280	16	32	94	187	280
	Tails	22	44	132	263	394	22	44	132	263	394	22	44	132	263	394	22	44	132	263	394
	TOTAL	72	144	429	855	1281	72	144	429	855	1281	72	144	429	855	1281	72	144	429	855	1281

ADVANCED SAFEGUARDS CONCEPTS

In Table 3 we include advanced safeguards concepts that U.S. DOE laboratory research teams[11] are exploring for unattended systems including the use of the operator's load cells and accountancy scales[12], the use of neutron detectors for enrichment and mass,[13] tracking of cylinders to ensure continuity of knowledge of a specific cylinder and its contents,[14] and advanced enrichment monitoring.[15] The IAEA proposed specifications for one such system with unattended flow monitoring and enrichment measurement capabilities as a Member State Support Program (MSSP) task to research systems and to propose developmental tasks to meet the stated performance goals. The IAEA derived the uncertainly specifications with a hope of duplicating or improving upon present attended NDA systems and developing some form of flow monitor. Installing for safeguards a flow monitor capable of measuring UF_6 flow at low pressures and flow rates would push present technology. The weight uncertainties for the MSSP specifications are much higher than those for using scales and load cells to find uranium mass. Hence, Concept B – MSSP SPEC in Table 3, contains these MSSP specifications. We also analyzed a DA sampling plan for P_D=10%. Since the unattended Concept B system would cover not just the required P_D=50% samples but 100% of all cylinders seen in the process over the course of the year, 100% flow verification should detect undeclared feed producing undeclared product for both LEU and HEU undeclared operations. We could relax DA sampling and just randomly check 10% of the flow to catch any bias defects that could signal a diversion. Hence, while the rise in uncertainty of mass (weight uncertainties) drives up the number of DA samples at P_D=50%, an assumption of the use of IDS by having 100% verification by NDA allows for a lower P_D. This lower P_D results in a decrease in the required number of DA samples (shown in parentheses in Table 3); this reduction becomes truly significant as plant capacity increases.

Concept C – NEUT DET in Table 3 couples passive neutron measurement capabilities provided by a proposed LANL-developed system to determine uranium mass and ^{235}U enrichment in UF_6 cylinders. The neutron detection system uses total neutron counting, assuming a known enrichment, to give the uranium mass in lieu of or to authenticate the load cell or accountancy scale mass data 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 principal source of neutrons in UF_6.[16] 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 neutron detection system 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). The neutron detection system would use a passive neutron enrichment monitor under development at LANL to determine uranium enrichment. It uses total neutron counting to verify the load cell mass. If a GCEP used reprocessed uranium, this technique might not be applicable.

The operators and especially the IAEA 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 AEM at the headers feeding or withdrawing from the cascades to measure the enrichment of UF_6. Hence, this system will determine the enrichment of the feed, product and tails without having to physically measure each cylinder. One of the challenges of the unattended system is to ensure 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. 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.

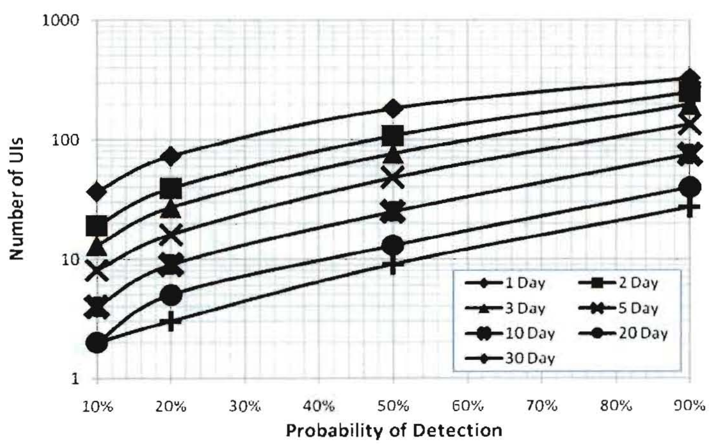
Table 3 shows the total numbers of measurements that must be performed annually for P_D=50% across the range of plant capacities. For comparison purposes, the numbers of DA samples required for P_D=10% are shown in parentheses for the unattended system concepts. The reasoning behind relaxing the bias defect P_D is that all the unattended systems will exceed the P_D=50% sample requirement and give P_D=100% by seeing all material passing through the plant. Hence, there is less need to see extremely accurate enrichment measurements since the undeclared LEU production scenario is covered and the undeclared HEU production is covered by enrichment monitoring of the feed, product, and tails. A bias defect P_D=10% would provide sufficient detection probability and deterrence by risk of early detection of HEU production.

In Table 4 we have taken the above systems and calculated what the sample sizes would be for P_D=20%, the IAEA's definition of random low sampling. Note that as in Table 3, the numbers of DA samples required for P_D=10% are shown in parentheses for the unattended system concepts. If the IAEA had sufficient confidence in the correctness and completeness of a State's declarations, a relaxation of the detection goal could be in order. The IAEA has means to do this with the AP and State Level Approach that provide increased transparency for a State's program. With AP in force the IAEA can give a State the Broader Conclusion. With the Broader Conclusion, the IAEA can assume no undeclared activities exist and institute Integrated Safeguards. Integrated Safeguards allows for relaxation of some safeguards efforts because of the increased transparency of the AP and the Broader Conclusion in place. Hence, while the IAEA has confidence that a State has no clandestine facilities, the IAEA still must have assurance that a declared facility is not being misused to create HEU. If the IAEA's environmental sampling program is completely effective and timely, an operator would be deterred from misusing a LEU GCEP for HEU production. However, if the operator can perform clandestine HEU production in such a clean fashion as to leave no trace of a small scale production of 1–2 SQs per year in a declared facility, the IAEA should consider other verification options. The most obvious option is to perform UIs. We can calculate the number of UIs, as shown in Figure 1, needed to get a reasonable P_D of clandestine HEU production. Factors that will influence the number of UIs are the scale of the plant, scale of the clandestine operation, and the duration/window of the undeclared activity. One can see that the number of NDA and DA measurements decreases dramatically by dropping P_D from 50% to 20% even in the attended system case. However, without assurance that HEU production is not occurring clandestinely a relaxation in the safeguarding of LEU may be imprudent. The results in Figure 1 show that with a short window for the operator to move to HEU production and back to LEU production a huge number of UIs are needed for even P_D=10%. Furthermore, if the undeclared activity can be completed over a weekend during non-business hours, a time free from even AP Complementary Access and present UI protocols at GCEPs, detection of the HEU production may approach zero.

TABLE 4: Sampling Plans for Advanced Safeguards Systems at P_D=20%

P_D=20%		Measurements/Inspection									
		A - ATTENDED STD HSP					B - UNATTENDED MSSP SPEC				
Type of Sample Measurements		500 MTSWU/yr	1000 MTSWU/yr	3000 MTSWU/yr	6000 MTSWU/yr	9000 MTSWU/yr	500 MTSWU/yr	1000 MTSWU/yr	3000 MTSWU/yr	6000 MTSWU/yr	9000 MTSWU/yr
NDA & Weighing	Feed	10	19	57	115	173	9	17	51	102	153
	Product	5	10	29	59	87	4	8	23	46	68
	Tails	5	10	27	55	82	4	9	26	52	77
	TOTAL	20	39	113	229	342	17	34	100	200	298
DA & Weighing	Feed	3	6	16	31	46	4(2)	8(4)	22(11)	44(21)	66(32)
	Product	1	2	5	9	14	2(1)	4(2)	11(6)	22(11)	33(16)
	Tails	3	6	19	37	55	4(2)	7(4)	20(10)	40(19)	60(29)
	TOTAL	7	14	40	77	115	10(5)	19(10)	53(27)	106(51)	159(77)
Total	Feed	13	25	73	146	219	13	25	73	146	219
	Product	6	12	34	68	101	6	12	34	68	101
	Tails	8	16	46	92	137	8	16	46	92	137
	TOTAL	27	53	153	306	457	27	53	153	306	457

P_D=20%		Measurements/Inspection									
		C - UNATTENDED NEUT DET					D -UNATTENDED AEM ACC				
Type of Sample Measurements		500 MTSWU/yr	1000 MTSWU/yr	3000 MTSWU/yr	6000 MTSWU/yr	9000 MTSWU/yr	500 MTSWU/yr	1000 MTSWU/yr	3000 MTSWU/yr	6000 MTSWU/yr	9000 MTSWU/yr
NDA & Weighing	Feed	11	21	62	125	187	12	24	70	141	211
	Product	4	9	25	51	75	5	11	32	65	96
	Tails	6	13	39	78	116	7	15	43	87	130
	TOTAL	21	43	126	254	378	24	50	145	293	437
DA & Weighing	Feed	2(1)	4(2)	11(5)	21(10)	32(15)	1(1)	1(1)	3(2)	5(3)	8(4)
	Product	2(1)	3(2)	9(4)	17(8)	26(13)	1(1)	1(1)	2(1)	3(2)	5(3)
	Tails	2(1)	3(2)	7(4)	14(7)	21(10)	1(1)	1(1)	3(2)	5(3)	7(4)
	TOTAL	6(3)	10(6)	27(13)	52(25)	79(38)	3(3)	3(3)	8(5)	13(8)	20(11)
Total	Feed	13	25	73	146	219	13	25	73	146	219
	Product	6	12	34	68	101	6	12	34	68	101
	Tails	8	16	46	92	137	8	16	46	92	137
	TOTAL	27	53	153	306	457	27	53	153	306	457



Window of Undeclared Activity (Days)	Probability of Detection			
	10%	20%	50%	90%
1	37	73	183	329
2	19	39	107	250
3	13	27	76	196
5	8	16	48	135
10	4	9	25	76
20	2	5	13	40
30	2	3	9	27

FIGURE 1: UIs to Detect HEU Production Driven by Time to Produce HEU

Hence, we can conclude that UIs for the detection of HEU production are only workable if the window of vulnerability is on the order of 20–30 days. Such long windows are only probable in small plants and not applicable to the GCEPs being built today around the world. Hence, the best solution is to have the unattended systems shown in Tables 3 and 4 above that would provide assurance of no undeclared LEU production or HEU production. An obvious benefit of the unattended systems is that in Concepts C and D, the numbers of DA samples at P_D=50%, 20% or 10% decrease significantly. If one can assume P_D=10% is valid because of the increased ability to detect clandestine LEU or HEU production, then the number of DA samples could be collected on 5–7 UIs during the year in which an inspector could check the unattended systems for tampering or service the unattended systems if they show anomalous results. Triggering these inspections on data, as proposed by Laughter[17], as well as performing them randomly is a first step. More analysis is needed to confirm if the systems' robustness and tamper indication will in practice reduce effort and costs at a GCEP.

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 and how the effectiveness of UIs as an alternative to scheduled inspections or unattended systems depends on the duration of certain diversion scenarios which can be a factor of the size and configuration of a GCEP. 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 inspection activities more effective by the use of unattended systems with reduced measurement uncertainties 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 unattended passive neutron mass measurement and enrichment monitoring systems can provide valuable process monitoring and accountancy data as well as the ability to verify if undeclared HEU is being produced in a more efficient and effective manner than by UIs depending on the time scale of a diversion. 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. Furthermore, a key concern is that rigorous evaluation of the safeguards approaches with respect to authentication must be done. We realize that the most significant point is that the whole system process flow should be examined with respect to vulnerabilities. If the process flow has vulnerabilities, the integrity of the authenticity of the data becomes unimportant.

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