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Gas Centrifuge Enrichment Plants Inspection Frequency and Remote Monitoring Issues for Advanced Safeguards Implementation

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Abstract. Current safeguards approaches used by the 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 high enriched uranium (HEU) production with adequate 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 cylinders of uranium hexafluoride that are used in the process of enrichment at GCEPs. This paper contains an analysis of how possible improvements in unattended and attended NDA systems including process monitoring and possible on-site destructive analysis (DA) of samples could reduce the uncertainty of the inspector's measurements providing more effective and efficient IAEA GCEPs safeguards. We have also studied a few advanced safeguards systems that could be assembled for unattended operation and the level of performance needed from these systems to provide more effective safeguards. The analysis also considers how short notice random inspections, unannounced inspections (UIs), and the concept of information-driven inspections can affect probability of detection of the diversion of nuclear material when coupled to new GCEPs safeguards regimes augmented with unattended systems. We also explore the effects of system failures and operator tampering on meeting safeguards goals for quantity and timeliness and the measures needed to recover from such failures and anomalies.

1. Introduction

The IAEA currently safeguards multiple large-scale LEU GCEPs in several countries with more facilities coming on line or expanding in the next few years. With an increase in the number and capacity of GCEPs, there is a need for the IAEA with its finite resources to be able to implement safeguards more effectively and efficiently. Three principal safeguards concerns for nuclear material diversions from LEU GCEPs include production and diversion of a significant quantity (SQ) of uranium with enrichment greater than declared (in particular, HEU), diversion of a SQ of declared uranium (particularly in the form of LEU product), and production and diversion of LEU in excess of declared amounts. The detection of undeclared HEU production is of greatest concern, since HEU can be directly used in nuclear weapons. The Hexapartite Safeguards Project (HSP) safeguards approach [1] 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, introduce undeclared UF_6 feedstock into a GCEP, and remove the undeclared product for use in an undeclared HEU cascade in the same facility or in a separate clandestine 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.[2] The IAEA moved in recent years to cover this gap in the HSP safeguards approach by rolling out a model approach which includes random inspections and the use of the "Mailbox" concept as safeguards tools to enable the detection of undeclared LEU operations.[3]

2. 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 [4], 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 Information-Driven Safeguards (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.[5]

These new instruments should attempt to decrease the uncertainties associated with NDA 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 SQ in the noise of measurement uncertainties. The operator will calculate the MUFs 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.[6]

3. 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, we 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. Our model facilities for analysis are facilities with ^{235}U enrichment of the feed = 0.711%, product = 5.0%, and tails = 0.34% for three cases scaled from 500 MSTWU/yr to 9000 MTSWU/yr. Table 1 includes yearly material flows and cylinder throughputs for three case study GCEPs that represent a range of enrichment plant capacities. This table illustrates that as plant capacity increases, the values of σ_{MUF} and the possibility for diversion of one SQ into MUF correspondingly increase.

Using the IAEA's methodology [7] we calculated the total number of measurements an inspector must perform annually to attain a required P_D including the total numbers of measurements required for each stratum, and the numbers of gross, partial, and bias defect measurements that comprise the total sample size. We have extended the methodology to other safeguards approaches—such as our three advanced unattended systems—and evaluated the potential efficiencies gained from their implementation. The base case analysis was the standard HSP inspector-attended inspection approach using the International Target Values [8] for instrument performance (Table 2 (Concept A - STD HSP) column) which we compared against the advanced safeguards approaches under development. Using a probability of detection of 50% (P_D=50%) as the nominal safeguards for a State with INFCIRC/153 safeguards and P_D=20% for a State with the AP in place, we have calculated for all three strata in Tables 3 and 4, respectively, the Concept A sample sizes.

Table 1. Yearly material and cylinder throughputs of facilities for study.

Nuclear Material Quantity	500 MtSWU/yr	3,000 MtSWU/yr	9,000 MtSWU/yr
Feed (Cylinders/yr)	115	690	2,070
Product (Cylinders/yr)	53	318	954
Tails (Cylinders/yr)	106	636	1,908
Feed (kgU/yr)	923,484	5,540,905	16,622,714
Product (kgU/yr)	73,522	441,132	1,323,396
Tails (kgU/yr)	849,962	5,099,772	15,299,317
Feed (kg^{235}U/yr)	6,566	39,396	118,187
Product (kg^{235}U/yr)	3,676	22,057	66,170
Tails (kg^{235}U/yr)	2,890	17,339	52,018
Feed (SQ/yr)	88	525	1,576
Product (SQ/yr)	49	294	882
Tails (SQ/yr)	39	231	694
σ_{MUF} (kg^{235}U)	13	79	236
σ_{MUF} (SQ)	0.18	1.1	3.2

Table 2. Advanced safeguards concepts target values (random and systematic uncertainties in % RSD).

Measurement and Stratum		ATTENDED STD HSP (A)		UNATTENDED MSSP SPEC (B)		UNATTENDED NEUT DET (C)		UNATTENDED AEM ACC (D)	
		u(r)	u(s)	u(r)	u(s)	u(r)	u(s)	u(r)	u(s)
NDA	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	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	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

Table 3. Sampling plans for advanced safeguards systems at P_D=50% (P_D=10% in parentheses).

Measurement		ATTENDED STD HSP (A)			UNATTENDED MSSP SPEC (B)			UNATTENDED NEUT DET (C)			UNATTENDED AEM ACC (D)		
		500 MtSWU/yr	3000 MtSWU/yr	9000 MtSWU/yr	500 MtSWU/yr	3000 MtSWU/yr	9000 MtSWU/yr	500 MtSWU/yr	3000 MtSWU/yr	9000 MtSWU/yr	500 MtSWU/yr	3000 MtSWU/yr	9000 MtSWU/yr
NDA	Feed	26	155	464	22	134	402	22	171	510	33	195	584
&	Product	14	80	238	10	60	178	10	67	200	15	89	266
Weight	Tails	12	75	223	12	70	208	12	110	329	21	125	373
	TOTAL	52	310	925	44	264	788	44	348	1039	69	409	1223
DA &	Feed	8	48	143	12(2)	69(11)	205(32)	6(1)	32(5)	97(15)	1(1)	8(2)	23(4)
Weight	Product	2	14	42	6(2)	34(6)	102(16)	5(1)	27(4)	80(13)	1(1)	5(1)	14(3)
	Tails	10	57	171	10(2)	62(10)	186(29)	4(1)	22(4)	65(10)	1(1)	7(2)	21(4)
	TOTAL	20	119	356	28(5)	165(27)	493(77)	15(3)	81(13)	242(38)	3(3)	20(5)	58(11)
Total	Feed	34	203	607	34	203	607	34	203	67	34	203	67
	Product	16	94	280	16	94	280	16	94	280	16	94	280
	Tails	22	132	394	22	132	394	22	132	394	22	132	394
	TOTAL	72	429	1284	72	429	1284	72	429	1284	72	429	1284

Table 4. Sampling plans for advanced safeguards at P_D=20% (P_D=10% in parentheses).

Measurement		ATTENDED STD HSP (A)			UNATTENDED MSSP SPEC (B)			UNATTENDED NEUT DET (C)			UNATTENDED AEM ACC (D)		
		500 MtSWU/yr	3000 MtSWU/yr	9000 MtSWU/yr	500 MtSWU/yr	3000 MtSWU/yr	9000 MtSWU/yr	500 MtSWU/yr	3000 MtSWU/yr	9000 MtSWU/yr	500 MtSWU/yr	3000 MtSWU/yr	9000 MtSWU/yr
NDA	Feed	10	57	173	9	51	153	11	62	187	12	70	211
&	Product	5	29	87	4	23	68	4	25	75	5	32	96
Weight	Tails	5	27	82	4	26	77	6	39	116	7	43	130
	TOTAL	20	113	342	17	100	298	21	126	378	24	145	437
DA &	Feed	3	16	46	4(2)	22(11)	66(32)	2(1)	11(5)	32(15)	1(1)	3(2)	8(4)
Weight	Product	1	5	14	2(1)	11(6)	33(16)	2(1)	9(4)	26(13)	1(1)	2(1)	5(3)
	Tails	3	19	55	4(2)	20(10)	60(29)	2(1)	7(4)	21(10)	1(1)	3(2)	7(4)
	TOTAL	7	40	115	10(5)	53(27)	159(77)	6(3)	27(13)	79(38)	3(1)	8(5)	20(11)
Total	Feed	13	73	219	13	73	219	13	73	219	13	73	219
	Product	6	34	101	6	34	101	6	34	101	6	34	101
	Tails	8	46	137	8	46	137	8	46	137	8	46	137
	TOTAL	27	153	457	27	153	457	27	153	457	27	153	457

4. Advanced safeguards concepts

The base case analysis showed that as the plant capacity 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, especially tails stratum samples.

Table 2 includes advanced safeguards concepts that U.S. DOE laboratory research teams [9] are exploring for unattended systems including the use of the operator's load cells and accountancy scales [10], the use of neutron detectors for enrichment and mass [11], tracking of cylinders to ensure continuity of knowledge of a specific cylinder and its contents [12], and advanced enrichment monitoring [13]. 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. The hope has been to develop an on-line unobtrusive flow meter. However, that has been an elusive technical goal for years. Concept B – MSSP SPEC in Table 2 contains these MSSP specifications.

Concept C – NEUT DET in Table 2 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. Uranium hexafluoride 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.[14] 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 NDA of 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, less need exists to see extremely accurate enrichment measurements since counting all cylinders coming in and out of the process covers the undeclared LEU production scenario and enrichment monitoring of the feed, product, and tails covers the undeclared HEU production scenario. 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 allow 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.

We can conclude that UIs for the detection of HEU production are only workable if the window of vulnerability to create one SQ of HEU is on the order of 20–30 days. Such long windows are only probable in small plants. Hence, the best solution for large production GCEPs is to have the unattended systems shown in Table 2 that would provide assurance of no undeclared LEU production or HEU production. An obvious benefit of the unattended systems is that Concepts C and D decrease the numbers of DA samples at P_D=50%, 20% or 10% significantly. If one can assume P_D=10% is valid because of the increased ability to detect clandestine LEU or HEU production, then the IAEA could collect the required number of DA samples during 4–7 UIs during the year in which an inspector could check the unattended systems for tampering or service them if they show anomalous results. Triggering these inspections on data analysis, as proposed by Laughter [15], as well as performing them randomly is a first step in defining how to use a remote monitoring capability to produce safeguards conclusions in a bulk handling facility. More analysis is needed to confirm if the systems' robustness and tamper indication will in practice reduce inspection effort and costs at a GCEP.

5. Consequences of remote system malfunction and recovery of inventory

The analysis in Section 3 shows how the advanced systems using unattended and remote systems can improve safeguards effectiveness and efficiency by reducing labour and increased ability to monitor flow through the facility. Laughter discussed using information sent from a remote site to the IAEA as a go/no-go system with colour-coded lights sending a status check to the IAEA that all systems are operating (state-of-health) and that all the data is reporting within nominal ranges. The IAEA would have the option of triggering inspections randomly or on system failures. We envision that a "yellow" light could signal partial system failure but that enough data is being collected to make material balance conclusions. Inspectors could trigger on yellow to check the system and fix the malfunctioning system components. "Orange" could signal a more serious case with the total loss of data from one or two strata of nuclear material. "Red" could signal the case of a loss of enough data to no longer be able to verify any stratum of material in the process. An analytical system could be used, as proposed by Howell [16,17], to massage the data and protect enough of it such that only needed inspection information transmits to the IAEA headquarters. Langner and MacArthur [18] have also designed data barrier systems to protect sensitive information from being revealed to an inspectorate. If the operator has continued concerns about the leakage of data, he may request that the data be sent in a form of "green–yellow–orange–red" coded go/no-go status lights to Vienna on a daily basis and that inspection data be sent on a less frequent basis. In this way, the IAEA would have neither more near-real time data than the operator nor knowledge of the daily operation of the GCEP. Such a system would preclude the release of sensitive data off-site but would have the disadvantage of not providing data to inspectors to ensure that the remote systems have actually performed the essential verification activities.

We have considered the consequences of system malfunction or detection of tampering and loss of data. We analyzed the consequences of the "red" failure mode in which the IAEA could not verify a diversion of an SQ of nuclear material. We assumed two cases for data transmission periods to the IAEA from the GCEP.

Table 5. Numbers of cylinders moving through the reference facilities following one or three system failures over the course of one year. System data transmission rates are weekly or monthly.

System Data Transmission Rate		500 MtSWU/yr		3,000 MtSWU/yr		9,000 MtSWU/yr	
		Cylinders Missed		Cylinders Missed		Cylinders Missed	
		1 failure	3 failures	1 failure	3 failures	1 failure	3 failures
Weekly	Feed	3	7	14	40	40	120
	Product	2	4	7	19	19	56
	Tails	3	7	13	37	37	111
	Total	8	18	34	96	96	287
Monthly	Feed	10	29	58	173	173	518
	Product	5	14	27	80	80	239
	Tails	9	27	53	159	159	477
	Total	24	70	138	412	412	1234

We analyzed two failure cases which in the lexicon of Laughter would be seen as "red" total failures with total data loss. The first case has data remotely transmitted to the IAEA on a weekly basis. The second case has data transmitted to the IAEA on a monthly basis. We chose these intervals because they reflect two possible solutions to operator concerns over sensitive data leaking from the site and concerns over the IAEA having real-time or near real-time abilities to monitor the process that would be seen as damaging to the operator's commercial interests or security. Table 5 shows that with weekly transmission there is little data lost with one failure per year for smaller-scale plants. Two product cylinders missed by the system represent approximately one SQ of material. If the operator must hold all processed cylinders until the IAEA declares from remote inspection that all Mailbox-declared cylinders have been verified and no undeclared activities have been seen, then the IAEA has a chance to verify the empty feed cylinders and full tails and product cylinders. Of course, as plant capacity increases the number of cylinders to be verified and the number of missed cylinders grows. With weekly data transmission and one failure per year, the capability of the system to detect undeclared activity is still passable. With a 9000 MTSWU/yr plant, one failure would yield over 16 SQs of unverified product moving through the plant during that week. If we assume an uncertainty of ±10% of the declared enrichment nominal capability of a GCEP, the operator could produce over one SQ of undeclared product in the week the system fails; this undeclared production activity would be lost in the noise of the plant.

Increasing the transmission interval from one week to one month reduces confidence in detection of undeclared activities. If the operator holds the full tails and product cylinders and the empty feed cylinders until the IAEA confirms satisfactory verification, verification of declared cylinders for the tails and product strata can be recovered. If the IAEA can see 11 of 12 months or 51 of 52 weeks of the declared feed throughput, it can have a decent understanding of the feed throughput. Further work will examine just how much data loss can be tolerated without substantially affecting confidence that no diversions of an SQ of product are occurring. Hence, we would desire for an optimal system to have a weekly transmission rate to avoid long "blackout" periods and significant loss of data especially of the feed. We note that with a partial system failure some UF_6 cylinder strata may be properly verified while others may not. If the product header enrichment monitor does not fail, HEU production detection capability would be maintained. If the product header enrichment monitor fails, then an UI for detection of HEU production would be in order. Hence, all natural UF_6 cylinders processed in the system could be verified properly while the tails and product verification data could be missing or corrupted. The incorporation of a global cylinder tracking network and tracking within the GCEP [19] could provide capabilities to enhance the ability of the operator and IAEA to resolve anomalies by narrowing down cylinder locations to assure no undeclared UF_6 is processed. Further research in this area will illustrate various failure modes and system vulnerabilities to determine how the IAEA might recover from less-than-total system failures. With operator concern that a remote safeguards inspection system might produce false alarms resulting in labour intensive anomaly resolution campaigns with the IAEA, such information is vital in order for both entities to evaluate the effectiveness and efficiency of remote systems such as our B, C, and D options and whether true increased effectiveness in safeguards will result from their implementation.

5. Conclusions

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 scale 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 enrichment process and accurate measurements of the enrichment and weights of UF_6 feedstock, tails, and product is 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 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 labour 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 detect the production of undeclared product 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 and possible system failures. In this paper we have shown our first attempts at understanding what the result would be to a remote inspection regime if the system failed and information were lost. We noted that failures of pieces of the system would not necessarily be catastrophic for the system as a whole. Analysis will be done to quantify the effects of various system failures and determine the duration of data "blackout" that can be tolerated. In our investigation so far we have seen that the loss of data for one month per year is the most that could be tolerated in smaller-scale facilities but that a failure lasting one week is the most a large-scale facility could sustain. Deploying an unreliable remote system that would bring into doubt the ability of the IAEA to reach its safeguards goals at a GCEP would create problems for the IAEA, the State, and the operator because of all the extra work required to investigate the anomalies resulting from false alarms and system failures. Hence, we will be intensely analyzing the system vulnerabilities, the integrity of the authenticity of the data, and system failure consequences to ensure the effectiveness and efficiency of advanced safeguards for GCEPs. Our analysis will quantify where redundancy of safeguards measures is essential and can lead to a more reliable and effective remote safeguards system.

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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] 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 of the INMM 50th Annual Meeting, Tucson, AZ, July 2009[3] 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.
[4] M. Zendel and N. Khlebnikov, "Optimizing and Joining Future Safeguards Efforts by 'Remote Inspection'," Proceedings of the 2nd JAEA-IAEA Workshop on Advanced Safeguards Technology for the Future Nuclear Fuel Cycle, Tokai-mura Ibaraki, Japan, November 2009.
[5] B.D. Boyer, H.H. Erpenbeck, K.A. Miller, M.T. Swinhoe, K. Ianakiev, and J.B. Marlow, "Analysis of the Effectiveness of Gas Centrifuge Enrichment Plants Advanced Safeguards," Proceedings of the INMM 51th Annual Meeting, Baltimore, MD, July 2010.
[6] *IAEA Safeguards Glossary*, 2001 edition, IAEA, Vienna, Austria, 2002.
[7] J.L. Jaech and M. Russell, *Algorithms to Calculate Sample Sizes for Inspection Sampling Plans, "Nuclear Safeguards* IAEA Report STR-261 (Rev. 1), Vienna, Austria, March 1991.
[8] H. Aigner, et al., *International Target Values 2000 for Measurement Uncertainties in Safeguarding Nuclear Materials*, IAEA Report STR-327, Vienna, Austria, April 2001.
[9] P.C. Durst, "An Analysis of Advanced Safeguards Approaches for New Large-Scale Uranium Enrichment Plants," Proceedings of the INMM 49th Annual Meeting, Nashville, TN, July 2008.
[10] 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 of the INMM 49th Annual Meeting, Nashville, TN, July 2008.
[11] 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, Los Alamos, NM, 2009.
[12] 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 of the INMM 49th Annual Meeting, Nashville, TN, July 2008.
[13] 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 of the INMM 49th Annual Meeting, Nashville, TN, July 2008.
[14] 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.
[15] M. Laughter, "Optimizing and Joining Future Safeguards Efforts by 'Remote Inspection'," Proceedings of the 2nd JAEA-IAEA Workshop on Advanced Safeguards Technology for the Future Nuclear Fuel Cycle, Tokai-mura Ibaraki, Japan, November 2009.
[16] J. Howell, T. Burr, and B. Boyer, "Mailbox-Centered Utilization of GCEP Station Load Cell Data," LA-UR 10-05451, Los Alamos National Laboratory, Los Alamos, NM, August 2010.
[17] J. Howell, T. Burr, and B. Boyer, "Comparing Accountancy Scale Full and Tare Product Cylinder Weights to Weights Obtained From Product Station Load Cells," LA-UR 10-05502, Los Alamos National Laboratory, Los Alamos, NM, August 2010.
[18] D. Langer and D. MacArthur, "An Application of Unattended and Remote Monitoring to Sensitive Systems," Proceedings of the INMM 45th Annual Meeting, Orlando, FL, July 2004.
[19] G. Eccleston, R. Babcock, J. Bedell, G. Cefus, D. Hanks, J. Jo, M. Laughter, J. Oakberg, M. Rosenthal J. Tape, and M. Whitaker, "Monitoring Uranium Hexafluoride (UF6) Cylinders ," ORNL/TM-2009/128, Oak Ridge National Laboratory, Oak Ridge, TN, June 2009.