A Monte Carlo Analysis of Weight Data from UF_6 Cylinder Feed and Withdrawal Stations*

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As the number of nuclear facilities handling uranium hexafluoride (UF_6) cylinders (e.g., UF_6 production, enrichment, and fuel fabrication) increase in number and throughput, more automated safeguards measures will likely be needed to enable the International Atomic Energy Agency (IAEA) to achieve its safeguards objectives in a fiscally constrained environment. Monitoring the process data from the load cells built into the cylinder feed and withdrawal (F/W) stations (i.e., cylinder weight data) can significantly increase the IAEA's ability to efficiently achieve the fundamental safeguards task of confirming operations as declared (i.e., no undeclared activities). Researchers at the Oak Ridge National Laboratory, Los Alamos National Laboratory, the Joint Research Center (in Ispra, Italy), and University of Glasgow are investigating how this weight data can be used for IAEA safeguards purposes while fully protecting the operator's proprietary and sensitive information related to operations. A key question that must be resolved is, what is the necessary frequency of recording data from the process F/W stations to achieve safeguards objectives? This paper summarizes Monte Carlo simulations of typical feed, product, and tails withdrawal cycles and evaluates longer sampling frequencies to determine the expected errors caused by low-frequency sampling and its impact on material balance calculations.

Keywords: GCEP Safeguards; load cell monitoring

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1. Introduction to load cell monitoring*

The International Atomic Energy Agency (IAEA) and safeguards experts are investigating monitoring of process load cells at enrichment plant feed and withdrawal (F/W) stations in an effort to strengthen IAEA safeguards [1, 2, 3, 4, 5]. As uranium enrichment plants increase in number and capacity, more unattended, automated safeguards measures are needed to enable the IAEA to maintain safeguards effectiveness while balancing fiscal constraints. Monitoring load cell data can significantly increase the IAEA's ability to efficiently achieve the fundamental safeguards objective of confirming operations as declared, but care must be taken to fully protect the sensitive or proprietary information related to operations. Limiting the frequency of data collection could be one approach to protecting the operator's information.

To use load cells as an effective process monitoring tool, the minimum data capture frequency necessary to count the number of UF_6 cylinders processed, to confirm full and empty cylinder weights, or to calculate inventory differences ("close the material balance") needs to be understood. To date, several arbitrary frequencies (e.g., every 10 min, every 30 min, or every 4 h) have been used in analysis and to discuss concepts of load cell monitoring. However, the ability to draw safeguards conclusions using certain load cell monitoring frequencies is driven by how long the various operational activities take at a facility.†

Uranium enrichment plants have three processes for transferring UF_6 material between the process and storage cylinders: feeding, product withdrawal, and tails withdrawal. The operational activities at each of these transfer stations have a slightly different cycle. Specific operation and times vary from facility to facility, but for this study, the following representative activities and times are used.

Feed Cycle

At a feed station, it takes a few minutes to load a full 48Y feed cylinder into the feed station. It then takes approximately 1.5 h to connect the hoses and purge the lines before the hatch to the feed station is closed. Once the hatch is closed, a purification process that removes light gases and other impurities can take 2–3 h. Depending on plant conditions, the station may be placed in standby until that particular feed is needed. When the feed in that cylinder is needed, the cylinder will begin transferring UF_6 into the process. The transfer time is dependent upon the size of the facility and the number of feed stations. For this paper, we have defined the feed time as 3.5 days. When the cylinder can no longer maintain the required process pressure, other cylinders will be connected to the process. During this phase, it can take about 4 h to remove as much of the heel material as possible. After the heel removal process, the cylinder may sit for up to a day with the door still closed depending on the availability of a location to place the empty cylinder. After the door is opened, the cylinder cools for about 3 h before the operators spend an hour purging and disconnecting hoses. Unless the station requires maintenance activities, the station remains empty for only a few hours before another feed cylinder is loaded in and the cycle begins again.

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* Some introductory information in this paper has appeared in earlier papers. This information is necessary to provide background to the current work.

†Higher data frequencies may also contribute to procedures for building confidence in the authenticity of the data.

Product Cycle

Model 30B cylinders are used for the product cycle. Once an empty 30B cylinder is loaded into a withdrawal station, it can take approximately 1.5 h to connect the cylinder. With the withdrawal station door closed, it takes one hour to chill the cylinder to temperature, and then the cylinder is often put into standby until needed. For this paper we have defined product fill period to be 5 days. While steps can be taken to minimize frost on the exterior of the cylinder during the withdrawal, if a cold cylinder is brought out of stations and exposed to air with water vapor, significant amounts of frost could form. Once full, a cylinder sits in the station for 8–10 h for the cylinder temperature to stabilize relative to the plant environment. Once the door to the station is open, it takes between 1 and 1.5 h to disconnect and remove the cylinder. Unless there is maintenance on the station, another product cylinder is loaded into the station within an hour.

Tails Cycle

After an empty tails Model 48Y cylinder is loaded into a withdrawal station, it takes approximately 1.5 h to connect it before the station door is closed. Similar to the product cycle, it takes an hour to chill the cylinder to temperature for it to be ready for filling, but the station could sit in standby for a few hours or days. Once online, a tails cylinder is filled in 4 days. In this paper the authors assume that once the cylinder is full, it defrosts inside the station for 8 to 10 h. After opening the station door, it takes approximately 1 to 2 h to disconnect and remove the cylinder from the station, which then sits vacant for less than an hour before another tails cylinder is loaded.

Load cell monitoring background

A typical F/W station at a modern plant could have a set of four load cells at each station connected to a summing board or junction box which is then connected to a weighing indicator. The weighing indicator provides an excitation voltage to the load cells and converts the response signal to an electronic weight reading that is communicated to a Programmable Logic Controller (PLC) [6]. This paper assumes the IAEA is recording weight data that is split from a PLC. Because the PLC is operator-owned equipment and each station is under the control of a central Supervisory Control and Data Acquisition System (SCADA), the PLC could forward weight and supplemental information such as the current phase of the cycle.

For feed cycles, this paper assumes the first data point above zero is the full weight and the last non-zero weight is the empty weight. For product and tails cycles, this paper assumes the first data point above zero is the empty or heels weight and the last non-zero weight is the full weight.

The weight profile for a tails cylinder as material is withdrawn from the process may resemble the plot shown in Figure 1. From a safeguards perspective, the amount of material transferred to or from a cylinder is more important than high frequency weight time series data. However, enough time series data should be provided to accurately record the full and empty weights (and contribute to authenticating the data). With infrequent data there could be considerable differences between the true empty weight value and the value the IAEA would interpret as the empty weight. This difference can be seen in Figure 1 where the red points show the data the IAEA would receive. The second red point from the left demonstrates that there can be a considerable difference between the true empty weight and the first data point the IAEA would receive after the cylinder was inserted.

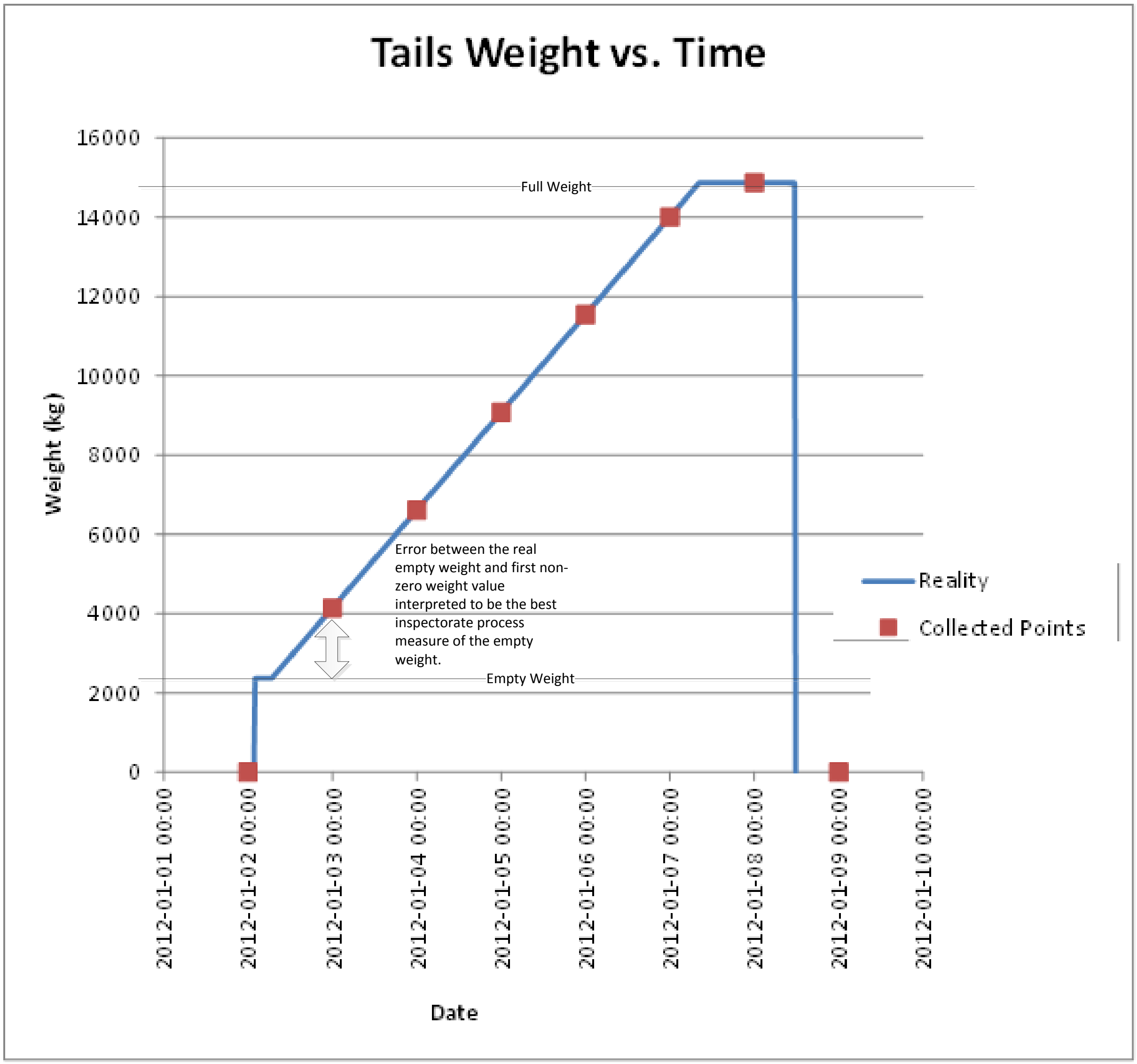

Figure 1. Weight data for a tails removal cycle if the inspectorate was provided with data at 24 hour intervals.

The authors have developed a mathematical model of F/W cycles to better define how data frequency affects the ability to identify the full and empty weights and calculate the material balance during F/W cycles. The model uses the @Risk plugin for Microsoft Excel[‡]. The @Risk plugin allows users to develop models in familiar Excel spreadsheet environments but perform Monte Carlo simulations to simulate many possible outcomes.

In the product and tails cycle example listed above, the author generalized that it takes 1.5 h to connect the hoses and purge the lines before the hatch to the station is closed, but the author suggests that sometimes the technicians can perform the task in 45 min, while other times it takes 4 h. The Program Evaluation and Review Technique (PERT) uses the beta distribution to model the duration of a task for Monte Carlo simulations [7]. The authors have used the PERT

[‡] http://www.palisade.com/risk/

distribution to model the time it takes to complete a task. A PERT distribution uses a minimum time for an activity along with a maximum time, and it skews the distribution between these end points using the most likely time. During a Monte Carlo simulation, @Risk samples from the distribution to generate a random duration for the time it took the technicians to connect and purge the hoses. For a limited number simulations, a histogram of the random durations that @Risk selected could vary widely from the PERT distribution, but as the number of iterations increases, the histogram should more closely resemble the distribution from which the durations were sampled.

The authors have configured a PERT distribution for each phase of the feed, product and tails cycles and used the @Risk package to sample from these distributions to simulate the duration of each phase to evaluate a set of representative cycles.

For feed cylinders, the authors define the “full” weight as the gross weight of the UF_6 cylinder and its contents before it is connected to the cascade and the “emptied” weight as the weight of the cylinder after it is emptied and the heel is minimized. This “emptied” weight may include some heel material and is expected to be slightly more [<10 kg (<~25 lb)] than the tare weight of the cylinder. For product and tails cylinders, the authors define the “empty” weight of a product or tails UF_6 cylinder as the gross weight of the cylinder before it is filled with material from the cascade. As described above, this weight may include some heel material. The authors define the “full” weight as the gross weight of the UF_6 cylinder after it is filled with material from the cascade.

Monte Carlo Results

A hypothetical 4000 tonne Separative Work Unit (SWU)/year gas centrifuge enrichment plant (GCEP) could use 9258 tonne of natural feed at 0.711% ^{235}U to enrich 1552 tonne of product UF_6 to 3.0% ^{235}U with 7706 tonne of tails depleted to 0.25% ^{235}U. If we assume the plant uses 48Y cylinders for feed and tails, and 30B cylinders for product, and each cylinder is filled to 95% of its full capacity, the plant would require about 780 48Y feed cylinders, 720 30B product cylinders, and 649 48Y tails cylinders (Figure 2).

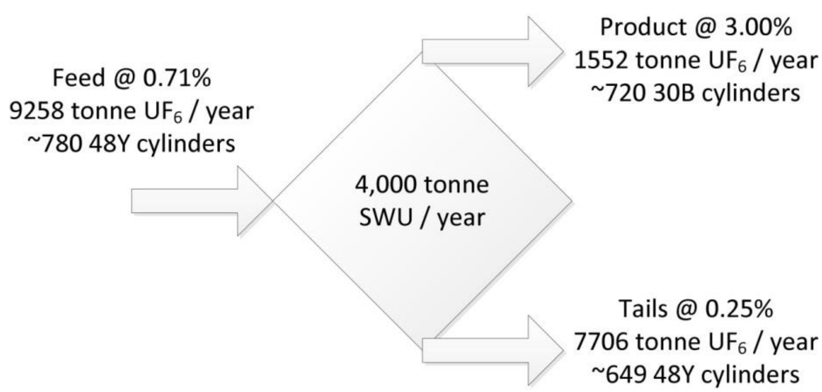

Figure 2: Cylinder requirements at a 4000 tonne SWU/year facility (The facility could use 780 48Y cylinders to produce 720 30B product cylinders at 3%, and 649 48Y tails cylinders at 0.25%.)

The Monte Carlo model was configured to represent feed, product and tails cycles. The data frequency was varied and the model was run until the results converged or until 50,000 iterations were performed. The results for feed cycles at different data frequencies are summarized below in Table 1. The results for product cycles at different at data frequencies are summarized below in Table 2. The results for tails cycles at different data frequencies are summarized below in Table 3.

Table 1. Kilograms of bias from low frequency data for 780 feed cylinders with hoses that have 0 kg impact

Data Frequency	Average bias from reality (kg) per cylinder	# Cylinders per year	UF6 bias (kg) per year	U bias (kg) per year	Enrichment	U235 bias (kg) per year
24:00	432.64	780.00	337,459.20	228,122.42	0.711%	1,621.95
12:00	85.12	780.00	66,393.60	44,882.07	0.711%	319.11
8:00	59.60	780.00	46,488.00	31,425.89	0.711%	223.44
6:00	45.24	780.00	35,287.20	23,854.15	0.711%	169.60
4:00	22.16	780.00	17,287.80	11,686.55	0.711%	83.09
3:00	10.17	780.00	7,932.60	5,362.44	0.711%	38.13
2:00	2.24	780.00	1,744.08	1,179.00	0.711%	8.38
1:00	-	780.00	-	-	0.711%	-
0:30	-	780.00	-	-	0.711%	-

Table 2. Kilograms of bias from low frequency data for 720 product cylinders with hoses that have 0 kg impact

Data Frequency	Average bias from reality (kg) per cylinder	# Cylinders per year	UF6 bias (kg) per year	U bias (kg) per year	Enrichment	U235 bias (kg) per year
24:00	(94.00)	720.00	(67,680.00)	(45,751.68)	3%	(1,372.55)
12:00	(11.57)	720.00	(8,330.40)	(5,631.35)	3%	(168.94)
8:00	(2.75)	720.00	(1,976.40)	(1,336.05)	3%	(40.08)
6:00	(0.64)	720.00	(460.80)	(311.50)	3%	(9.35)
4:00	0.04	720.00	28.56	19.31	3%	0.58
3:00	0.05	720.00	35.28	23.85	3%	0.72
2:00	0.01	720.00	4.77	3.23	3%	0.10
1:00	-	720.00	-	-	3%	-
0:30	-	720.00	-	-	3%	-

Table 3. Kilograms of bias from low frequency data for 649 tails cylinders with hoses that have 0 kg impact

Data Frequency	Average bias from reality (kg) per cylinder	# Cylinders per year	UF6 bias (kg) per year	U bias (kg) per year	Enrichment	U235 bias (kg) per year
24:00	(518.49)	649.00	(336,500.01)	(227,474.01)	0.25%	(568.69)
12:00	(67.72)	649.00	(43,950.28)	(29,710.39)	0.25%	(74.28)
8:00	(17.56)	649.00	(11,396.44)	(7,703.99)	0.25%	(19.26)
6:00	(5.17)	649.00	(3,355.14)	(2,268.07)	0.25%	(5.67)
4:00	(0.50)	649.00	(323.01)	(218.35)	0.25%	(0.55)
3:00	0.01	649.00	6.24	4.22	0.25%	0.01
2:00	0.01	649.00	4.10	2.77	0.25%	0.01
1:00	-	649.00	-	-	0.25%	-
0:30	-	649.00	-	-	0.25%	-

The results for a mass balance at the model facility are given in Table 4. For our hypothetical 4000 tonne SWU/year GCEP, as highlighted in yellow, if uncertainties are ignored and data is only recorded every 24 hours:

- **The accountancy data for feed cylinders would reflect 1622 kg more ^{235}U was transferred to the process than the process data would reflect;**
- **The accountancy data for product cylinders would reflect 1373 kg less ^{235}U was transferred from the process than the process data would reflect;**
- **The accountancy data for tails cylinders would reflect 569 kg less ^{235}U was transferred from the process than the process data would reflect;**
- **So, the accountancy data would reflect 3563 kg more ^{235}U inventory in the process material balance area (MBA) than the process data.**

Table 4. Mass balance summary for a 4000 tonne SWU/year facility with hoses that have 0 kg impact.

Data Frequency	Feed Bias U235 (kg)	Product Bias U235 (kg)	Tails Bias U235 (kg)	Mass Balance U235 (kg)
24:00	1,621.95	(1,372.55)	(568.69)	3,563.19
12:00	319.11	(168.94)	(74.28)	562.33
8:00	223.44	(40.08)	(19.26)	282.78
6:00	169.60	(9.35)	(5.67)	184.62
4:00	83.09	0.58	(0.55)	83.06
3:00	38.13	0.72	0.01	37.40
2:00	8.38	0.10	0.01	8.28
1:00	-	-	-	-
0:30	-	-	-	-

2. Comparison with uncertainty values

We expect 9 kg of uncertainty in each weight measurement of a 48Y using the process load cells cells[11]. For feed cycles, when data is being collected every two hours or more frequently we expect less bias than uncertainty, but the bias contribution from a small subset of outlier cycles may be non-trivial. Similarly, for tails withdrawal cycles, when data is being collected every six hours or more frequently we expect less bias than uncertainty, but the bias contribution from a small subset of outlier cycles may be non-trivial.

We expect 1.8 kg of uncertainty in each weight measurement of a 30B using the process load cells [11]. For product withdrawal cycles, when data is being collected every six hours or more frequently we expect much less bias than uncertainty, but the bias contribution from a small subset of outlier cycles may be non-trivial.

The IAEA defines a significant quantity of low-enriched uranium as 75 kg ^{235}U, 10 tonne natural U or 20 tonne depleted U.[10].

For the reference 4000 tonne SWU/year facility that handles approximately 780 feed cylinders, 720 product cylinders and 649 tails cylinders per year, the total uncertainty for an annual mass balance if the process scale data accurately reflected the appropriate full and empty weights should be 486 kg UF_6 or 2.27 kg ^{235}U [11].

As shown in Table 4, to ensure the bias in process load cell data results in an inventory difference less than a significant quantity, a period of 3 h or less should be used. For instance, at 3 h sampling the inventory difference due to sampling frequency should be approximately 37 kg ^{235}U.

Other Considerations

The weight of hoses or other connections can drastically affect the mass balance. In the preceding analysis, the weight of the hoses was assumed to be counterbalanced and have 0 kg effect. However, if the hoses add 7 kg to the weight after they are connected, the mass balance can be drastically affected. For instance, as shown in Table 5, when the mass of the hoses is 7 kg, the bias grows drastically even for short sampling periods. This bias effect occurs when either the first non-zero point that we must interpret to be the full (feed) or empty (product or tails) weight occurs after the hoses have been connected, and the last non-zero point occurs after the hoses have been disconnected or vice versa.

This additional bias could be minimized if weight data is taken more frequently whenever the station door is open, or by triggering a weight data point immediately after the station door or hatch is opened or closed. Potentially, a fixed frequency could be used and supplemented with a triggered weight data point. The triggered weight data point would accommodate mass balance calculations, and the periodic weight data would facilitate confidence in the authenticity of the data.

Table 5. Mass balance summary for a 4000 tonne SWU/year facility with hoses that have 7 kg impact.

Data Frequency	Feed Bias U235 (kg)	Product Bias U235 (kg)	Tails Bias U235 (kg)	Mass Balance U235 (kg)
24:00	6,373.31	(1,369.63)	(566.49)	8,309.43
12:00	1,266.10	(154.78)	(72.16)	1,493.04
8:00	895.37	(21.90)	(17.81)	935.08
6:00	679.41	16.50	(3.82)	666.73
4:00	351.48	39.42	2.56	309.50
2:00	103.53	71.55	5.37	26.60
1:00	77.10	77.39	5.75	(6.04)
0:30	52.86	52.57	3.95	(3.66)

Potentially different data taking rates could be used for different stations types. As shown in Table 1**,** a data taking rate of 4 h for feed stations could result in a bias of more than a significant quantity. However, as shown in Table 2 and Table 3, a data taking rate of 6 h for product and tails stations provides an expected bias much less than one SQ. Therefore, a 2 h data taking rate may be required for feed stations, but a 6 h data taking rate may be sufficient for product and tails stations.

Conclusion

A challenge for the current GCEP safeguards approach is the ability to effectively detect the introduction of undeclared UF_6 feed. This paper demonstrates a potential solution through the use of unattended load cell data. The frequency of the data transmissions will be a key factor in determining how to protect the operators' proprietary information. Process load cell monitoring could be one tool in the IAEA's tool box and may not necessarily be deployed/utilized at all GCEPs, and in all cases would require host country/operator consent. Process load cell data could be integrated with other safeguards measures (e.g., mailbox declarations, accountancy scale data, OLEM, UCVS, etc.) to make safeguards more effective and efficient.

The authors must caution that this analysis is heavily dependent on how the plant is operated and does not analyze the impact to the material unaccounted for (MUF) calculation as a result of an operator trying to divert into MUF.

If the distributions used to model the duration of each phase are representative and reasonable, this analysis shows that for a 4000 tonne SWU/year facility with weight data provided every hour or two, the systematic bias annually from feed and withdrawal station data will be more than the measurement uncertainty.

This analysis also shows that load cell data collected every hour or two could be considered a continuity-of-knowledge tool to be used in conjunction with accountancy scale measurements. It may be possible to use the process load cell full and empty weights as confirmatory measurements about the operator's weights reported from their typically higher precision accountancy scales. These confirmatory measurements would allow the IAEA to calculate the inventory difference using the accountancy scale values with more confidence. Data between these confirmatory measurements provide the IAEA with a sense that no undeclared cylinders were processed on these stations. As presented in "A Monte Carlo Analysis of Gas Centrifuge Enrichment Plant Process Load Cell Data"[11], the uncertainty associated with each process load cell weight is actually larger than the average systematic error due to missing the cooling and/or standby phase.

At larger plants, the number of cylinders used over the course of a year would likely be greater than the numbers used in this study. This would increase the uncertainties in material balance calculations from process load cell data. To counteract this, each enrichment unit or module could be treated as a separate MBA, or the material balance could be calculated more frequently.

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References

[1] Cooley JN, et al. "Model safeguards approach and innovative techniques implemented by the IAEA at gas centrifuge enrichment plants." *Proceedings of 48th Institute of Nuclear Materials Management Annual Meeting*, Tuscon, Ariz. 2007.

[2] Howell J, Burr T, Boyer B. "Counting GCEP feed cylinder throughput from load cell data." *ICFO-SI 9 – The 9th International Conference on Facility Operations-Safeguards Interface*, Savannah, Georgia, Sept. 23–28, 2012, on CD-ROM. American Nuclear Society, LaGrange Park, Ill., 2012.

[3] Howell J, Friend P, Jones D, Taylor C. "Load-cell-based mass evaluation systems re-assessed on the basis of URENCO (Capenhurst) load cell data." ESARDA Meeting, Lithuania, 2009.

[4] Carchon J, Dechamp L, Eklund L G, Janssens W, Mercurio G, Peerani P, and Richir P. "Load Cell Monitoring in Gas Centrifuge Enrichment Plants: Potentialities for Improved Safeguard Verifications." *Nuclear Engineering and Design* 241, no. 1 (2011): 349-56.

[5] Garner JR, Gilligan KV, Henkel JJ, Hooper DA, Krichinsky AM, Lockwood D, Rowe NC, Whitaker JM, Younkin JR. "New Measures to Safeguard Gas Centrifuge Enrichment Plants." *Proceedings of the ESARDA Symposium*. 2011.

[6] Garner JR, et al. "Leveraging the intrinsic features of off-the-shelf weighing indicators to build confidence in international safeguards measures." *Proceedings of the INMM Annual Meeting.* 2012.

[7] URL http://www.palisade.com/risk/monte_carlo_simulation.asp.

[8] https://measurementsensors.honeywell.com/ProductDocuments/Load/Model_129_Datasheet.pdf

[9] *Mettler Toledo Weigh Module Systems Handbook*. Mettler Toledo, Columbus, Ohio.

[10] *IAEA Safeguards Glossary 2001 Edition*, International Nuclear Verification Series No. 3; International Atomic Energy Agency, Vienna, 2002.

[11] Garner JR, Whitaker JM. "A Monte Carlo Analysis of Gas Centrifuge Enrichment Plant Process Load Cell Data." *Proceedings of the ESARDA Symposium*. 2013.

[12] Garner JR,; "A Monte Carlo Analysis of Gas Centrifuge Enrichment Plant Product and Tails Withdrawal Station Load Cell Data." *Proceedings of 55th Institute of Nuclear Materials Management Annual Meeting*, Atlanta, Ga. 2014