SCIENCE & GLOBAL SECURITY
2017, VOL. 25, NO. 2, 59–79
https://doi.org/10.1080/08929882.2017.1318563

Timely Verification at Large-Scale Gas Centrifuge Enrichment Plants

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ABSTRACT

This article examines challenges in international nuclear safeguards pertaining to the timely detection of highly enriched uranium production at large-scale gas centrifuge enrichment plants. To establish where present gas centrifuge enrichment plant safeguards measures and approaches could be strengthened, we have created a discrete time model for simulating hypothetical misuse scenarios, both through transient phases and at steady-state. We find that timely detection of misuse at modern large-scale facilities presents a challenge for international safeguards. A toolbox of unattended measurement systems, along with remote monitoring, however, could be used to improve detection timeliness, enabling the initiation of follow-up activities, potentially on a rapid time scale. These measures, which would need very low false alarm rates, should be implemented in a graded approach, depending on the characteristics of each enrichment plant and an analysis of plausible acquisition paths for the State in which it is situated. Some of these technologies could provide significant benefit to plant operators.

ARTICLE HISTORY
Received 11 October 2016
Accepted 10 April 2017

Introduction

International Atomic Energy Agency (IAEA) safeguards activities at gas centrifuge enrichment plants (GCEPs) are a crucial component of the verification regime for the Treaty on the Non-proliferation of Nuclear Weapons (NPT). In implementing the NPT verification regime, the IAEA undertakes safeguards activities under the authority of Comprehensive Safeguards Agreements (CSAs) in non-nuclear weapon states (NNWS). CSAs delineate a set of measures for the implementation of safeguards on all nuclear material within the borders, jurisdiction, or control of NNWS, pursuant to the NPT. On this basis, nuclear material at GCEPs in NNWS is subject to IAEA safeguards activities.[1] In addition, safeguards activities are also carried out at civil GCEPs in nuclear weapon states, under Voluntary Offer Agreements concluded between those States and the IAEA. GCEPs can be misused to produce

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Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/gsgs.

unirradiated direct use material, in this case highly enriched uranium (HEU), which can be used, after chemical and metallurgical processing, in fabrication of a nuclear weapon without further changes to its isotopic content. Thus, verification activities at large-scale commercial GCEPs (as opposed to pilot-or laboratory-scale facilities) are particularly important, as the capacity of these plants significantly reduces the timescale over which consequential misuse could occur. The IAEA aims to provide timely detection of the following scenarios at uranium enrichment plants[2]:

- Diversion of natural, depleted or low-enriched uranium hexafluoride from declared flow in a facility
- Misuse of a facility to produce undeclared product from undeclared feed
- Misuse of a facility to produce uranium hexafluoride at enrichments higher than the declared maximum, especially highly enriched uranium

This article examines the timely detection of the third scenario, in which a large-scale GCEP is misused to produce HEU. In addition, while the analysis in this article is directly applicable to IAEA safeguards, it could also be important for verification of a future Fissile Material Cutoff Treaty, or other treaties limiting the amount of military fissile materials. If military fissile material stockpiles shrink in nuclear weapon states (NWS), it may become increasingly important to verify the absence of any fissile material production in NWS.

Following from a simple idealized calculation, there is a clear need for timely verification of possible misuse at large-scale GCEPs. The production of one significant quantity (SQ) of 90%-enriched weapons-grade HEU[3] starting from 8.9 t of naturally enriched uranium hexafluoride (UF_6) requires approximately 5,400 kilograms of separative work (kgSWU), or 5.4 tSWU, assuming a product enrichment of 90% and a tails enrichment of 0.30%. (Note that the mass in the definition of separative work is uranium mass, not UF_6 mass.) Starting from 0.87 t of 5%-enriched UF_6, only 1.2 tSWU are required, with a tails enrichment of 0.71%. A single commercial 4000 tSWU/year plant, capable of fueling about 30 1 GW(e) nuclear reactors, could, in this idealized calculation, produce 2.0 SQ of 90%-enriched uranium per day continuously from natural UF_6 feedstock. Alternatively, using an on-hand supply of 5%-enriched UF_6, ideally it could produce 9.1 SQ of weapons-grade HEU per day before consuming its stock of feed material. One month's prior production of 5%-enriched uranium would be 69t of UF_6, so 80 SQ could be produced in 8.8 days, using this supply. A similar calculation for a 500 tSWU/year plant yields 10 SQ in 8.8 days. Either of these scenarios would present a very serious challenge for timely detection and deterrence of the misuse of nuclear technology for the manufacture of nuclear explosive devices, the fundamental goal of IAEA safeguards.

Basing an estimate of a facility's potential for misuse solely on idealized capacity, however, does not yield realistic results. The physical layout of a given GCEP as well as the size, number, and arrangement of production units and cascades, play a significant role in evaluating practical misuse scenarios. Time and effort are significant factors. Some misuse scenarios require an impractical amount of manpower and take a very long time to execute, and are thus less attractive. There is also the question of how long it takes for a cascade, or a system of cascades, to equilibrate after reconfiguration, or after the feed assay is changed. To establish where present safeguards measures and approaches could be strengthened, while accounting for the above issues, we have considered a basic plumbing diagram for a reference large-scale gas centrifuge enrichment plant. We have also created a simple discrete time model for estimating cascade behavior during, hypothetical GCEP misuse scenarios, both through transient phases and at steady state.

The article begins with a discussion of sample scenarios, and we consider the plumbing diagram of a reference GCEP to determine practical misuse. We also estimate the time required for a new reconfigured system, with a new feed assay, to come to equilibrium, based on the discrete time model. The next section assesses the potential signatures of these misuse scenarios. Then a potential toolbox of unattended verification technologies is outlined. Lastly, we briefly examine the process of timely response in the context of IAEA verification of the NPT.

Sample scenarios

This section examines how misuse scenarios might be implemented at a reference gas centrifuge enrichment plant. For our sample scenarios, we consider cases where a GCEP is used to produce large quantities of weapons-grade uranium[4] as quickly as possible without detection.[5] Since direct access to weapons-usable material is provided through such scenarios, they place the greatest stress on the question of timeliness, more so than the diversion of natural, depleted or low-enriched uranium, or the excess production of LEU. Production of highly enriched uranium also would be most relevant in the context of a future Fissile Materials Cutoff Treaty (FMCT).

In a 2013 article, Smith, Lebrun, and Labella introduce a "reference" gas centrifuge enrichment plant, with nominal 4000 tSWU/year capacity.[6] The reference plant is made up of eight "units," each consisting of ten cascades. One unit is illustrated in Figure 1. Each unit has a header connection area, where cascade headers are joined to form unit headers, as well as a bank of UF_6 feed and withdrawal stations. Each unit has a nominal 500 tSWU/year enrichment capacity, while each cascade has a nominal 50 tSWU/year capacity. For round numbers, we assume that each centrifuge has a nominal 50 kgSWU/year capacity, and thus each cascade is

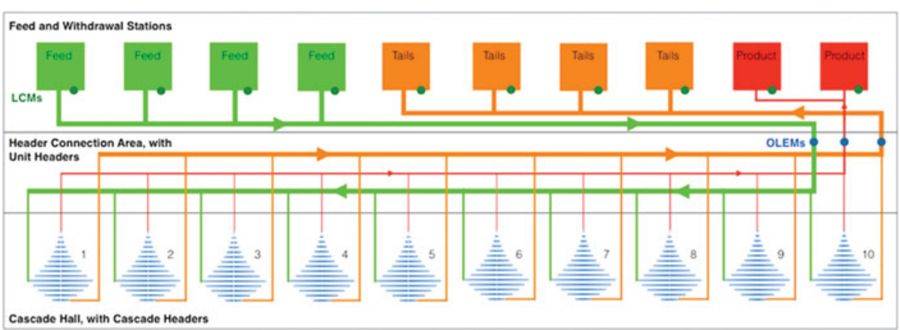

Figure 1. Simplified "plumbing diagram" for a single 500 tSWU unit of a reference gas centrifuge enrichment plant. The number and position of feed and withdrawal stations is arbitrary.

made up of 1000 centrifuges. We assume that these centrifuges operate with gain at each stage of $\gamma = \alpha\beta = 1.2^2$, where $\alpha = R'/R$ and $\beta = R/R''$, and relative isotopic abundance R is defined as:

$$R(N) = \frac{N}{1-N} \tag{1}$$

in which N is the atomic fraction of uranium-235 relative to the total uranium atomic abundance at a given point in a cascade. By convention, R and N without single prime ($'$) or double prime ($''$) markings represent material fed into a given stage. A single prime marking following R or N designates upflow from a stage, and a double prime marking indicates relative abundance and enrichment values for downflow from a stage. Note that all enrichment values given in this article are by atomic (molar) fraction, and not by weight.

A scenario where with $\alpha = \beta = 1.2$ allows a cascade to enrich material from 0.72% uranium-235 to 5.11% in eleven stages under ideal operating conditions. Assuming four stages of these same centrifuges on the stripping side, the tails are produced with an enrichment value of 0.29%. To estimate the equilibration time of the cascades, we assume that each centrifuge contains 10g of uranium, or about 14.8g of UF_6. Material in pipes between centrifuges is ignored, as it can be inferred from previous studies that the amount of material in piping is small (less than approximately 10%) relative to the amount of material in centrifuges.[7]

There are several potential approaches for misusing an enrichment plant to produce weapons-grade uranium.[8] In our sample scenarios we assume that the operator chooses to maintain the integrity of the individual cascades (not moving centrifuges between cascades) but does place the cascades into a new series-parallel configuration. For simplicity and scalability, and to avoid long interconnections, we further assume that the operator maintains the integrity of the individual units, neither moving cascades between units, nor making connections between units. Enriched UF_6 produced in some units can be transferred, in cylinders, to other units.

An operator planning to misuse an enrichment facility would encounter the problem that the higher cascades in a linked "cascade of cascades," composed of cascades designed for enrichment to 5%, are incorrectly shaped for their tasks. Optimally efficient cascades designed for higher enrichments have a blunter shape (i.e., have relatively more centrifuges in higher stages) than do cascades for lower enrichments. In this scenario, the operator might re-plumb centrifuges within a cascade into the ideal, blunter, configuration to maximize efficiency. This could, however, entail a significant amount of physical work in the centrifuge hall, which would require labor, time, materials and supplies, and considerable advance preparation, resulting in the risk of early detection. A quicker and perhaps less detectable alternative might be to "prune" centrifuges from the cascades, which involves removing centrifuges from service to form the ideal shape, at the cost of reducing the separative work available. This could also require significant labor, depending on the operational properties of the cascades. Approximately two thousand centrifuges would be need to be removed from service out of the ten thousand assumed to compose a unit. It should be recognized that remotely operable valves and/or otherwise flexible cascades and centrifuges could simplify these scenarios.

A quick and simple option, however, would be to leave the cascades in their original configuration, and feed them at their nominal mass flow rate, but at higher enrichment, while leaving all cut values unchanged. This modestly reduces the separative capacity of the cascades relative to their nominal capacity (at an ideal state), due to mixing of flows with differing enrichment, but, perhaps surprisingly, increases their overall enrichment gain. Conservation of total uranium atoms and atoms of uranium-235 in a single centrifuge or cascade stage can easily be shown to require:

$$\theta = \frac{(1+\alpha R)\,(\beta-1)}{(1+R)\,(\gamma-1)} \tag{2}$$

where θ is the "cut" or fraction of the feed atoms going into the product, and R is the ratio of uranium-235 to uranium-238 atoms in the feed to the centrifuge or stage. For $\alpha = \beta$, equation 2 reduces to the well-known formula for the ideal cut,[9]

$$\theta = \frac{1+\alpha R}{(\alpha+1)\,(1+R)} \tag{3}$$

Equation 3, incidentally, shows that the ideal cut grows with R, explaining the blunter shape at higher enrichment. On the other hand, for operation with a non-ideal cut, θ, defined by optimization for lower enrichment, equation 2 shows the necessary relationship between α and β. We assume that the stage separation factor $\gamma = \alpha\beta = R'/R''$ is, or can be arranged to be, approximately independent of θ and R, ignoring any other non-ideal effects that may be associated with operating at higher enrichment. Since α and β are both modestly above unity, the (β – 1) term provides the dominant variation on the right-hand side of equation 2, so β falls below α as θ falls below the ideal value. This is what happens when a cascade configured for a lower enrichment level is fed with material of higher enrichment. (It is well known,[10] and simple to see physically, that as the limit $\theta = 0$ is approached, β must approach unity and so α must approach $\alpha\beta$.) With higher α and lower β, a cascade will produce more highly enriched product. This makes it possible to traverse from LEU suitable for use in power reactors to material of enrichment above 90% in only two groups of unmodified cascades, as shown in Table 1, rather than the three groups typically assumed for ideal cascades.[11] This two-step non-ideal approach can achieve 90% enrichment using cascades with 11 enriching stages (as assumed here),

Table 1. Sets of cascades in abrupt diversion scenario.

	Feed Enrichment	Product Enrichment	Tails Enrichment	tSWU/year
Original	0.72%	5.11%	0.29%	50
Mid Group	5.11%	34.0%	2.29%	49.5
Top	34.0%	94.1%	28.1%	28.4

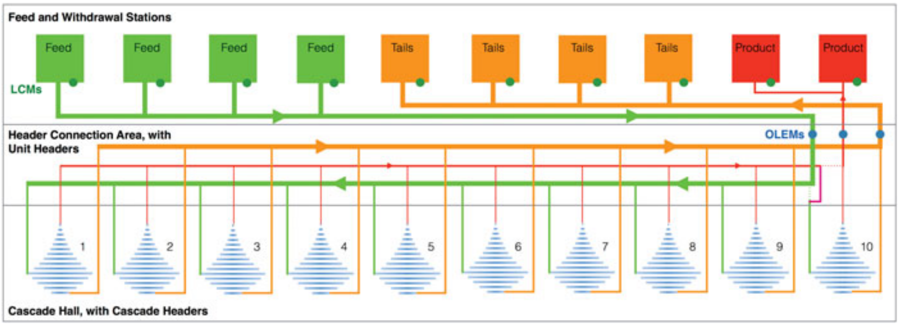

Figure 2. Simplified plumbing diagram for a single 500 tSWU unit of a reference gas centrifuge enrichment plant, modified in the vicinity above cascade #10 to produce HEU. New and replacement piping in magenta; piping appears as dotted lines.

but capable of product enrichment of only 4.6% and $\alpha = \beta = 1.19$. With $\alpha = \beta = 1.2$, as in this case, the minimum enrichment of LEU feedstock required to achieve 90% enrichment is 3.7%.

The ratio of feed to product flow in these cascades is uniformly 11.2. Thus, a single ten-cascade unit could be reconfigured to have nine mid group cascades feeding directly into a single top cascade, leaving some capacity to spare in the top cascade. To implement this scenario, shown in Figure 2, only two modifications would be needed in the header connection area.

1) The unit feed header would need to be disconnected from the cascade #10 feed header, but could otherwise remain unmodified, connected to all of the other cascade feed headers and to all of the feed stations.
2) The unit product header would need to be broken between cascades #9 and #10, and connected to the #10 cascade feed header.

The cascade #10 product header would feed unmodified into the remainder of the unit product header and so on to the product withdrawal station. Remarkably, no other changes would be required.

A question arises as to what the operator would do with the tails from the mid group and top cascades. Ten stripping stages (rather than the installed four) would be required for the tails to emerge from a given cascade at the same enrichment level as a lower cascade's feed. We assume that an operator trying to execute an abrupt diversion of weapons-grade HEU would judge that the addition of these stages would be too time-consuming, so instead the tails from the higher cascades would be captured and stored for recycling. The fastest approach, requiring the least modification of the system, would be simply to leave the existing tails cascade headers exactly as they are, continuing to feed the unit tails header, itself unmodified, and capture the tails from the mid-group and top cascade together. This approach is somewhat inefficient, since it mixes flows of different enrichment. It is, however, expeditious, optimally simple, and yields LEU of only a modestly lower enrichment than the material that is fed into the unit. This material can therefore be used to supplement the feed to the mid group, which is discussed in further detail later in this section.

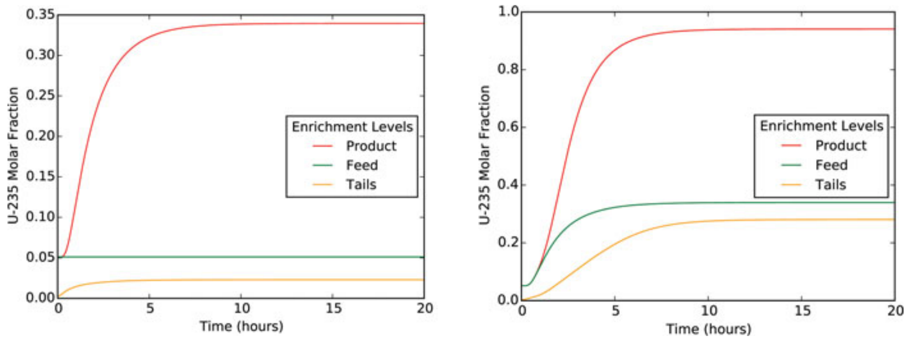

Figure 3. Time evolution of product, feed and tails uranium-235 concentrations of the mid group cascades (left) and the top cascade (right).

Once the cascades are reconfigured, the next step is to bring them to equilibrium at their new operating point. Figure 3 shows calculations of the time evolution of their feed, product, and tails enrichment levels (if tails are not recycled in this case). We have developed an explicit time-stepping model to carry out these calculations. The model calculates both flows and material assay in a cascade, given a set of user-specified characteristics, including cascade shape and cuts, centrifuge hold-up, and operating parameters. In this case, the model assumes that total molar flow through each centrifuge is constant, but with time-varying enrichment. This obviates the need for new hydrodynamic modeling, since no mass flows are changing significantly. Thus, all of the isotope-summed centrifuge and cascade flows are retained. Given the molar flow rates at each time step, the model calculates the amount of material (in moles) and enrichment level in each stage during each time step.

During each time step, the flow of material out of each stage is calculated first. The amount of material (in moles) that remains in each stage during a time step, m_{ret}, is given by:

$$m_{ret} = m_{s,t} - (L_{s,t}{}' + L_{s,t}{}'')\Delta t \tag{4}$$

where $L_{s,t}{}'$ and $L_{s,t}{}''$ are respectively the molar flow rates for material moving to the stages above and below during the timestep, $m_{s,t}$ is the stage holdup, and Δt is the length of the timestep. We assume ideal stage flow rates for the original cascade enrichment, unconstrained by the granularity of individual centrifuges.

Next, the enrichment of the material retained in the stage, N_{ret}, can be calculated, by:

$$N_{ret} = \frac{N_{s,t}m_{s,t} - (L_{s,t}{}'N_{s,t}{}' + L_{s,t}{}''N_{s,t}{}'')\Delta t}{m_{ret}} \tag{5}$$

where $N_{s,t}$ is the average molar enrichment of material in a stage (as opposed to in the feed) at the beginning of the time step, assuming immediate and full mixing, and $N_{s,t}{}'$ and $N_{s,t}{}''$ are respectively the enrichments of material moving to the stages above and below during the timestep, such that

$$N_{s,t}' = \frac{\sqrt{\gamma}R_{s,t}}{1 + \sqrt{\gamma}R_{s,t}} \tag{6}$$

and

$$N_{s,t}'' = \frac{R_{s,t}}{\sqrt{\gamma} + R_{s,t}} \tag{7}$$

where

$$R_{s,t} = \frac{N_{s,t}}{1 - N_{s,t}} \tag{8}$$

$R_{s,t}$ represents the average molar ratio of uranium-235 to uranium-238 inside the stage of a given stage, s, at time t. Note that we are assuming γ to be constant, since we are not allowing for any change in the total molar flows, and we are ignoring any higher-order changes associated with enrichment level.

The mass and enrichment of material in each stage at the end of a time step is calculated, by also including the inflow of material,

$$m_{s,t+\Delta t} = (L_{s-1,t}' + L_{s+1,t}'' + F_{ext})\Delta t + m_{ret} \tag{9}$$

$$N_{s,t+\Delta t} = \frac{(L_{s-1,t}'N_{s-1,t}' + L_{s+1,t}''N_{s+1,t}'' + F_{ext}N_{ext})\Delta t + N_{ret}m_{ret}}{m_{s,t+\Delta t}} \tag{10}$$

where the subscripts *s-1* and *s+1* denote the stages immediately below and above stage *s*, respectively, F_{ext} is the mass flow rate of feed material at the feed stage (F_{ext} is zero at all other stages), and N_{ext} is the feed enrichment.

In a situation where a cascade shape is sharper than ideal for the enrichment at which it is operating (e.g., the case at hand where the enrichment is higher than the design value) a smaller flow of enriched material is sent from a given stage to stages above because the cut is too low, and a greater flow of depleted material is sent to stages below, relative to the ideal case. The result is that the enrichment of the material in the centrifuges trends upwards over time relative to the enrichment of their feed. When equilibrium is reached, the values of α and β, calculated from the enrichment of the feed, product and tails of each stage, are found to be in excellent agreement with equation 2—even though α and β relative to the average of the material inside the centrifuges remain, by construction, at 1.2.

Equilibration takes place quite rapidly with the assumed inventory of UF_6 per centrifuge. As shown in Figure 3, the product enrichment of the top cascade crosses 90% after approximately 6 hours, and equilibrates to approximately 94% enrichment in 12 hours. Operating parameters common to original, mid group and top cascades are given in Table 2. A step time of 8 seconds was used for this simulation.

It is important to note that these estimates only consider losses in separative capacity due to the mixing of flows containing different enrichments. These calculations do not account for higher-order effects that may become significant at higher enrichments, and thus production figures given in this article should be taken to be approximate, but still illustrative of the time scale on which GCEP misuse can occur.

Table 2. Operating parameters for a 50 tSWU reference cascade producing LEU.

Stage	Initial stage enrichment, N_s,0	Stage Cut, θ_s	Stage flow rate, L_s (g UF6/s)	Stage holdup, m_s (g UF6)
−4	0.35%	0.4549	5.89	615.73
−3	0.42%	0.4549	10.80	1129.48
−2	0.50%	0.4550	14.90	1558.46
−1	0.60%	0.4551	18.33	1917.01
0	0.72%	0.4552	21.20	2217.12
1	0.86%	0.4553	17.14	1792.89
2	1.03%	0.4555	13.76	1439.11
3	1.24%	0.4557	10.94	1144.04
4	1.48%	0.4559	8.58	897.85
5	1.77%	0.4562	6.62	692.36
6	2.12%	0.4565	4.98	520.72
7	2.53%	0.4568	3.61	377.23
8	3.02%	0.4573	2.46	257.10
9	3.61%	0.4578	1.49	156.33
10	4.30%	0.4585	0.68	71.57

Two limiting-case misuse scenarios are now outlined. The first is a scenario in which pre-existing stocks of LEU (5%-enriched material) are fed into a plant with all units modified in the simple manner described above, until the LEU stocks run out. In the second scenario, some units are left unmodified and continue to produce LEU for feeding into two modified units. Both scenarios take advantage of tails recycling in the modified units. While the first scenario allows for faster production of weapons-grade material per unit of plant capacity, as separative work is only applied to enriching LEU to weapons-grade uranium (and not to enriching natural uranium to LEU), production can only continue as long as stocks of LEU last. The second scenario, on the other hand, allows for continuous production of weapons-grade material, but at a slower rate, as the plant is effectively enriching natural uranium to weapons-grade, instead of LEU to weapons-grade. For both types of misuse, it should be noted that the top cascade will be slightly starved of material, as the feed-product ratio of each cascade is 11.2, but the top cascade only has 9 cascades feeding it. Thus, the top cascade will produce HEU at $9/11.2 = 80.4\%$ of its capacity. The product flow rate for an ideal 50 tSWU/a cascade enriching natural uranium to 5.11%-enriched material is about 77 mol/day. Running at an 80% capacity factor, the top cascade will produce about 62 mol/day, which is roughly equivalent to 0.5 SQ/day at 90% enrichment. The number of moles in an SQ of HEU, however, is inversely proportional to enrichment, as the SQ is defined as 25 kg of uranium-235 in an undefined amount of HEU. Thus, at product enrichments higher than 90%, production rates in terms of SQ will be slightly higher, and vice versa for enrichments lower than 90%. Additionally, it is well known that operating a countercurrent centrifuge at a feed rate below the optimum level increases the machine's gain.[12] Thus, SQ production rates and product enrichments may be slightly higher than reported in this article, working to offset neglected higher-order effects.

For the fastest production scenario, a fully reconfigured (nominal) 4000 tSWU/year plant, with one month's plant production of 5.11%-enriched uranium on hand, can theoretically produce about 11 SQ of weapons-grade material in about 3 days, including equilibration time (but not re-configuration time), based on the model presented here. The tails from this process, including those collected during equilibration of the first cycle, could be recycled through the unit in two further cycles, theoretically allowing for a total production of approximately 29 SQ of weapons-grade material in about one week. Both the amounts that can be produced, and the production time, vary linearly with respect to the pre-existing stockpile, making this a very important factor. The maximum production rate, however, remains theoretically at 4.4 SQ/day for the whole plant. A 500 tSWU/year unit, considered as a stand-alone facility starting from one month's production of LEU produced solely by that unit, could theoretically produce 3.6 SQ in 7.3 days.

In a steady misuse scenario, 2 units can be reconfigured in the 8-unit reference facility as described above, with tails recycled from the modified units into their own feeds along with the feed from the 6 unmodified units. Doing this would naturally reduce the enrichment of feed going into the mid group, as well as the enrichment of material produced by the top cascade. Because the enrichment of the combined tails of the mid-group and top cascades is only slightly depleted relative to the mid group feed and because the original scenario had some margin above 90% enrichment, however, it is possible to still produce weapons-grade material when recycling tails material. (The precise result is 89.1% enrichment, but this does not consider the reduced feed to the top cascades and their resulting higher gains.) In this case 31 SQ per month (i.e., approximately 1 SQ/day) could nominally be produced at a continuous rate as long as natural UF_6 is supplied to the plant.

The production rates in these two scenarios correspond to approximately factor of 2 reductions from the highly idealized calculation presented in the introduction (which considered neither practical reconfiguration options nor equilibration times) both in total product from a given stored quantity of LEU and in production rate. Nonetheless, these more realistic results still constitute a significant challenge for timely verification, based on minimal reconfiguration effort required.

It is important to recognize that these calculations represent limiting cases. A potential proliferator, for example, could choose to modify fewer than 8 units, and produce the same amount of HEU from stored LEU over a longer period. Alternatively, a proliferator could choose not to recycle the tails from the modified units in either scenario. There are even mixed scenarios where the proliferator desires to produce the maximum material over a given period, say one month, so starts by processing existing LEU in modified units but also produces additional LEU during this time. Evidently there is a balance that could be struck between amount of modification effort (and associated risk of detection) and rate of production of material before detection.

Potential signatures

Before discussing the utility of safeguards measures in detecting the misuse of large GCEPs in the following section, it is important to assess the signatures that could be detectable during a misuse scenario, indicating off-normal operation at a facility.

Clearly, in both misuse scenarios, enrichment levels in the feed, product, and tails unit headers would be higher than in normal operation. In a modified unit, LEU would be present in the feed and tails unit headers, and HEU would be present in the product unit header. Feed and tails cylinders (e.g., 30B- or 48Y-type) containing LEU, as well as cylinders containing HEU, would be present in process areas. We calculate that it would be possible for a proliferator to feed standard LEU product cylinders with HEU (at the required 8% of the standard capacity, since it would be fed by a single cascade operating at 9/11.2 flow rate) in withdrawal cells without exceeding criticality limits.[13] Traces of HEU, which would be detectable by environmental sampling, would materialize in process areas. The presence of LEU at feed and HEU at withdrawal stations would result in higher levels of neutron radiation per unit mass of UF_6 in those areas, due to higher levels of uramium-234 in process material, as alpha particles emitted by uramium-234 induce an (α,n) reaction in fluorine contained in UF_6.[14] The time rate of change of this neutron emission could not be masked by operating with smaller masses of total UF_6. Piping reconfigurations (as described previously) would also be necessary either in the header connection area, or the cascade hall. This could be accomplished via the installation of piping between sample ports already installed in the process area, or via the construction of new ports or connection points. If the latter option involves making openings in existing pipework that has carried UF_6, the release of some UF_6, and the products of UF_6 hydrolysis, uranyl fluoride (UO_2F_2) and hydrogen fluoride (HF), would be likely. Takeoff points closer to the centrifuges than the feed/withdrawal areas may also be installed, possibly in the header connection area or in cascade halls. Visible evidence of reconfigured pipework may or may not exist, depending on the location of the activity.

Header flow rates would be abnormal: the flow rate in the product unit header outside the header connection area would be dramatically reduced to 8% of normal. The flow rate in the unit's feed header would nominally be 10% below normal (as only 9 of 10 cascades would be fed from that header). The tails unit header would carry a slightly lower-than-normal flow rate, as although it would be receiving the tails of 10 cascades, the tails output of the top cascade would reflect that it is slightly starved of feed. The fill rates of withdrawal cells, and the emptying rates of feed cells would also reflect these flow rates, particularly if undeclared feed and takeoff points exist.

Inconsistencies could emerge in the handling of UF_6 cylinders within the plant. Tails recycling would involve the movement of containers from withdrawal cells into feed cells, which should not happen at an enrichment plant under normal operation. In the fast production scenario, LEU stocks are used, which might necessitate the movement of full product cylinders from storage into a process area, which would be a sign of abnormal activity. A signature of a continuous operation scenario would be the frequent movement of full UF_6 cylinders between units. These cylinders might be full product cylinders, although feed cells may be designed only to accept larger feed/tails cylinders, thus necessitating the transfer of UF_6 from product containers into larger cylinders, perhaps using product blending equipment, modified as necessary. Regardless of cylinder type, LEU in these cylinders would not be available for verification, as it would have been fed into a modified unit.

Additionally, if product cylinders are used to feed a modified cascade instead of feed/tails cylinders, the changeout frequency of cylinders in feed cells would be higher than usual. Operator load cell data in feed cells, if available to an inspectorate, would reflect this.

Finally, inconsistencies would emerge in plant operations at a higher level. During a covert misuse scenario, a proliferator might physically conceal UF_6 cylinders (product, feed, and tails) containing off-normal enrichments. If safeguards authorities believe a plant is operating at the time of misuse, then the absence of material in product and tails cylinders commensurate with the plants declared production would constitute cause for further investigation. In a continuous scenario, LEU production and shipments would necessarily cease or be significantly reduced, as LEU product from unmodified units would need to be fed into modified units. By contrast, in a fast production scenario, unmodified units would still be able to produce product LEU as normal, which the facility would be able ship out, albeit at lower rates that would be inconsistent with normal operation. Nevertheless, prior to a fast production scenario, an operator may enrich LEU to higher levels (e.g., 5%) than would be produced under a normal operational scenario, in which a larger range of LEU enrichments might be produced. If material balance records were falsified in any of these scenarios to reflect normal facility operations, clear discrepancies would be apparent between these figures and observable material.

Toolbox of verification technologies

The objective of IAEA Comprehensive Safeguards Agreements is defined as "the timely detection of diversion of significant quantities of nuclear material from peaceful nuclear activities to the manufacture of nuclear weapons or of other nuclear explosive devices or for purposes unknown, and deterrence of such diversion by the risk of early detection."[15] In this section we outline a toolbox of potential unattended verification technologies that could be implemented to provide timely detection of signatures listed in the previous section, and therefore deterrence against the sample and related scenarios defined previously. The implementation of a subset of such systems would need to be undertaken with a graded approach, depending on the capacity and technology of the specific enrichment plant, the results of acquisition path analysis for the State (which considers the presence or absence of a broader conclusion providing increased assurance of the absence of undeclared nuclear material and activities in a State), and the degree, if any, of international management and engagement. These systems could improve not only the effectiveness but also the efficiency of safeguards, since inspector visits could be driven and focused more by unattended measurements and less by the calendar, possibly resulting in a reduced burden on operations. Importantly for operators, product cylinders may also be able to be released without delay for human inspection. These systems would complement the IAEA's existing verification framework, which includes periodic interim inventory verification, an annual physical inventory verification (PIV), containment and surveillance measures, and complementary access in Additional Protocol States. The GCEP safeguards approach developed through the Hexapartite Safeguards Project (HSP) also features limited frequency unannounced access (LFUA) inspections to cascade halls, during which inspectors may verify that cascade piping and configurations are consistent with design information and declared enrichment levels, either by visual inspection or by using instrumentation.[16] LFUA activities, in particular, are especially powerful tools for detecting the presence (and verifying the absence) of misuse activities at GCEPs as they may be called on very short notice, and inspectors may access process areas during these inspections that would otherwise be off-limits during implementation of other verification activities. A GCEP operator and the IAEA will typically agree on an average number of LFUA inspections to be held each year. Some of these LFUA activities take place in conjunction with routine inspection visits, while others are scheduled on a random basis, entirely separate from routine inspections. We propose here that, in addition, data from multiple unattended systems indicating off-normal conditions at a GCEP could provide impetus for an LFUA-type inspection of process areas, through which IAEA inspectors would verify the actual status of operations at the facility.

Smith, Lebrun, and Labella propose three technologies for unattended safeguards at their large "reference" enrichment plant: on-line enrichment monitors (OLEM), load cell monitors (LCM), and unattended cylinder verification stations (UCVS).[17] Here we briefly describe these technologies, and their relevance to our sample scenario.

On-line enrichment monitoring systems

On-line enrichment monitoring systems[18] are non-intrusively attached to unit headers, as shown in Figure 1. They may be attached to the product, feed and tails headers of each unit, so the reference GCEP discussed in the sample scenarios would be equipped with 24 such systems. By use of photon emission measurements, with appropriate calibration to remove the effects of pipe deposits, these systems can determine to a few percent accuracy the density of uranium-235 in the gas flowing through the unit header. Using temperature measurements on the outside of the header pipe and pressure sensors within the IAEA's tamper-indicating enclosure, the density of UF_6 gas can be inferred, allowing for an accurate assessment of the enrichment level of the gas in the unit header pipe. This technology has been qualified for application, and is currently under deployment.[19] OLEM systems could also provide co-benefits to GCEP operators, as enrichment measurements from these devices could be used for process control.[20]

Load cell monitoring

Load cell monitoring consists of time-dependent measurement of the mass of UF_6 cylinders in all feed and withdrawal stations attached to each of the unit headers, as shown in Figure 1. This measurement would be carried out by the facility operator and it would be challenging for the IAEA to verify the authenticity of this measurement independently. LCM measurements, combined with OLEM measurements, would allow near real-time closure of both the total mass balance and uranium-235 mass balance of each unit. The requirements for a technology to allow reliable sharing with the IAEA of information from load cell monitors are under development.[21] Load cell data may be considered commercially sensitive by operators, and thus establishing protocols for acquiring and handling this information may be challenging.

Unattended cylinder verification stations

Unattended cylinder verification stations would measure the total uranium mass in feed cylinders arriving at a GCEP, as well as uranium mass in product and tails cylinders ready to be shipped out of a GCEP. UCVS mass measurements could be used to independently and remotely verify data from accountancy scales shared by the operator with the IAEA. In addition, UCVS would measure the mass of uranium-235 contained in cylinders via neutron singles and doubles count rates, driven by the proxy of naturally occurring uranium-234 that is enriched along with uranium-235. UCVS would give assurance that all the material that passes through the unit headers, and is perhaps even mixed into final product cylinders, is sent out of the plant to the expected recipient. The technologies that can be used for UCVS are under development and qualification.[22]

Discussion of proposed unattended verification technologies

Smith, Lebrun, and Labella argue that OLEM, LCM, and UCVS together would provide much improved effectiveness of safeguards, by monitoring both total and uranium-235 mass balances in near real time, and assuring with high accuracy that activities at a GCEP are consistent with its declared, peaceful use.[23] These unattended technologies would also provide improved efficiency, most evidently because an effective UCVS system, combined with effective containment and surveillance measures, could allow product cylinders to be approved for removal from a GCEP without the physical presence of inspectors. UCVS would also, therefore, provide the non-proliferation benefit of reducing the normal on-site inventory of enriched UF_6 and, in conjunction with appropriate containment and surveillance, provide the IAEA with better knowledge of this inventory.

In principle, this suite of technologies could detect the scenarios outlined here if an operator allows feed, product, or tails material to pass through OLEMs in a modified unit, or does not tamper with load cell monitors (which would be recording off-normal feed and withdrawal rates for that unit). However, an operator may attempt to evade detection. An evasion scenario could involve blocking off and circumventing OLEMs before misuse takes place, so that the OLEMs only "see" enrichments reflecting normal operating conditions at the facility. In addition, an operator could tamper with load cell data (which cannot yet be authenticated by the IAEA), so that it reflects normal operating conditions, either by falsifying the data directly, or by using artificial weights to spoof the unloading and loading of feed and withdrawal cylinders respectively. A lack of LEU product cylinders being fed through one or multiple UCVS systems might indicate anomalous activity, but as these cylinders may not instantly be transported from the process area to the storage area once they are filled, evidence of facility misuse from a UCVS may only become indicative after production of many SQs of HEU has taken place. For example, under normal conditions, filled product cylinders might undergo homogenization in autoclaves in the process area, requiring a few days thereafter to cool.[24] Thus, detection of this scenario depends on the load cell monitors, which are not under the full control of the IAEA, and do not constitute fully independent measurement sources.

The load cell spoofing and blocking of OLEMs discussed above, however, could be made ineffective through the installation of flow monitors at feed/withdrawal stations and at OLEM installation points.

Unit header and feed/withdrawal flow monitors

We suggest that unattended technology for measuring the mass flow of UF_6 at the location of the OLEMs and the feed/withdrawal stations should be developed. The possibilities range from non-intrusive but quite complex, such as using a pulsed thermal neutron source to drive fission and detecting the delayed arrival of fission products downstream, to intrusive but simple, such as installing a differential pressure measurement device across a restriction in the header pipe.[25] Several technologies between these two extremes might be envisioned, perhaps based on sound wave propagation upstream vs. downstream in the UF_6 gas. The combination of OLEMs plus reliable unit header and feed/withdrawal station flow measurements, both under IAEA seal, would constitute a powerful verification tool. Like data from load cell monitors, however, information from these flow monitors may give rise to confidentiality concerns, and attention must be paid to maintaining the confidentiality of data measured by these devices. To mitigate data confidentiality and security concerns, flow measurement devices could be designed to transmit only binary "state-of-health" and "go/no-go" signals to IAEA Headquarters.

In the misuse scenarios described in this article, however, all the unattended safeguards measures could be circumvented (particularly when only binary signals are transmitted) if the operator were to falsely inform the IAEA that one or more units were being taken off line for maintenance, as the non-operation of portions of a facility could plausibly explain concurrent "no-go" signals from OLEM and LCM equipment. If this were to happen under normal operation with sufficient frequency, for example during the start-up of a GCEP, or regularly for preventive maintenance, it would be onerous for the IAEA to follow up each time, possibly undertaking an LFUA to the relevant cascade hall to confirm that no reconfiguration was underway. Thus, it may also be very desirable for the IAEA to have unattended means to quickly detect the reconfiguration of piping, in order to minimize requests for time-consuming inspections that are expensive for both the IAEA and the operator. Here we present a potential toolbox from which the IAEA might select, depending on the characteristics of an enrichment plant.

Unattended detection of reconfiguration

The IAEA, via a facility's design information questionnaire and design information verification, should be aware of the presence of all sample ports installed in cascade halls and in exterior process areas where pipes carry UF_6 to and from unit headers. The IAEA should be able to identify the combination(s) of these sample ports that could be used to re-pipe cascades into parallel/series configurations of concern. It may be possible to install remote tamper-indicating seals on critical ports, and an operator may agree to inform the IAEA prior to accessing these ports. If an unusual number of these critical ports were accessed, this could be an additional factor for the IAEA to consider in deciding whether to request an on-site inspection.

Cascades can also be reconfigured through the installation of new ports. Inevitably this process would result in exposure of some uranium hexafluoride, UF_6, to water vapor, resulting in the formation of uranyl fluoride (UO_2F_2) as particulate matter, and hydrogen fluoride (HF) gas. At the initial reconfiguration, when the IAEA would remotely detect this activity to provide timely detection and deterrence, the uranyl fluoride will not be enriched beyond the design value of the plant, so—for the purpose at hand—detection of HF is just as valuable as detection of UO_2F_2. This is fortuitous because HF is easier and quicker to detect, and not as easily contained as locally deposited uranyl fluoride particles. HF may also be released if an attempt is made to install a flow loop through a flow monitor and OLEM to spoof legitimate readings, while routing process material around the monitors. Commercial open path gas detection systems based on eye-safe lasers can sample path lengths greater than 100m.[26] Some study will be required to optimize a system, and to determine the degree to which an operator can avoid HF production, but it may be possible, by careful location and design, to detect the breaching of relevant piping with high confidence, while not suffering false alarms due to routine operations such as cylinder replacement. Measurements of unusual HF emissions could potentially be used to help motivate on-site inspection activities, possibly featuring access to process areas.

If the piping to a cascade were reconfigured, in general the activity would be visible, unless the required reconfiguration can be achieved using remotely operable valves without visible indication. Cameras could be located strategically, or could be scanned, to allow sightlines that view the relevant cascade headers and piping leading to and from the unit headers, but do not reveal sensitive information. Software could be used to detect changes in configuration and the presence of personnel, and indicate such changes and personnel presence, without releasing images of the piping configuration. This would parallel, in effect, measures currently used by inspectors during cascade hall access, where visual inspection is compared against photo albums of the verified configuration, stored at the facility under IAEA seal. Again, it would be important to confirm an extremely low false alarm rate, as well as high reliability of detection. Weaker but simpler alternatives (or complements) would be to use motion detectors rather than cameras, or to aim cameras at areas in the near vicinity of the piping, required to access the piping, but not the piping itself.

Monitoring of UF_6 cylinders

While the low density of material in centrifuges and cascade piping makes it challenging to measure neutrons even from cascades of centrifuges,[27] cylinders containing kilogram quantities of highly enriched UF_6 produce neutrons at much higher rates, as well as indicative gamma spectra. In a misuse scenario, unattended neutron and gamma detectors permanently located at feed and withdrawal stations could effectively detect the presence of LEU at feed and tails withdrawal stations and of HEU at product withdrawal stations. A proliferator, then, may choose to entirely avoid using installed feed and withdrawal cells to service modified portions of a facility, and instead feed and withdraw uranium using takeoff points in the header connection area, or within a cascade hall. These undeclared feed and withdrawal points could also be detected with unattended neutron and gamma measurements. Unattended neutron and gamma portal monitors could be located at access points to the header connection area and to cascade halls. More speculatively, between inspections, robots could be programmed to "rove" through the relevant regions of enrichment plants, carrying both neutron and gamma detectors. Alternatively, monitors could be configured to travel on rails above areas where illicit cylinders might be located. If a mobile monitor either detected anomalous radiation signatures, or was prevented from entering a normally accessible area, it could signal this situation. This would provide motivation for the IAEA (likely along with other detected signatures) to call for an on-site inspection. If such an inspection featured LFUA activities, inspectors could also carry radiation detection instruments to verify the absence of hidden feed and withdrawal cylinders.

Timely data transmission

Operators are sensitive to the detail and rate of data transmission from their facilities, both to avoid proliferation of sensitive technologies, and to protect their commercial interests. Thus, it will be necessary to limit the transmission of data, and likely even the accumulation of data within the systems discussed here. Although much more analysis is required, it appears that a simple two-bit transmission from each deployed monitoring instrument indicating state-of-health and "nominal operation" or "human verification required," perhaps every 6 hours, might be sufficient. As with the choice of technologies from the proposed toolbox, the frequency of data transmission should be graded, in this case depending particularly on the potential rate of production of weapons-grade material.

Timely response by IAEA

The IAEA has at its disposal two powerful tools for timely detection and response. The first is the ability to hold an on-site inspection with LFUA activities at facilities under HSP-type safeguards. This gives IAEA inspectors, with as little as two-hours notice, access to cascade halls at enrichment plants. Although LFUA inspections are typically held either in conjunction with routine inspections or on a random basis, if the IAEA were to detect off-normal activity through multiple independent signals, an LFUA could also be justified. Since it is unlikely that many large GCEPs will be constructed in the immediate future, and since those that are constructed are likely to be in or near states with other facilities under IAEA safeguards, designated inspectors could be stationed to be able to arrive promptly. The capacity and technology of the specific enrichment plant, the results of acquisition path analysis, the presence of a broader conclusion in the host state and the degree, if any, of international management and engagement should be considered by the IAEA in deciding on a request for a short-notice LFUA vs. further inquiries and discussion. It is clearly of the utmost importance, for the credibility of the IAEA and for the efficient operation of enrichment plants, that measurement-driven requests for short-notice LFUAs be extremely infrequent.

If evidence of significant misuse were to be detected during on-site inspection activities, or inspector access were to be inhibited, the Department of Safeguards would attempt to resolve the situation on a technical basis at an appropriate management level of the applicable State or Regional Authority responsible for safeguards implementation, while informing the IAEA Director General. If necessary, the Director General might contact the Foreign Minister of the state in question and request an expeditious resolution. As an ultimate step, the Director General could call a meeting to consult with the IAEA Board of Governors on very short notice, even a few hours, thus making the situation known to all. The possibility of such a chain of events should function as a powerful deterrent.

Summary and recommendations

Large-scale gas centrifuge enrichment plants present a substantial challenge to the goal of timely detection and deterrence of the production of weapons-grade uranium. The steps of reconfiguration, equilibration, and production of the first SQ of weapons-grade uranium would be slower than an ideal SWU calculation of production rate would suggest. However, the reconfiguration could perhaps be accomplished in hours or a very few days, and the subsequent production rate could be large. Fortunately, on-line enrichment monitors are now being deployed, and other technologies are currently under development. Given current supply conditions, an expansion of large GCEPs will likely be delayed, so it should be possible to implement these more effective safeguards that also allow for more efficient plant operation.

We recommend, nonetheless, that some further technologies be considered, to provide the IAEA with a sufficient toolbox for timely decision-making, based on multiple signal paths. Flow measurements under IAEA seal as a complement to OLEMs and LCMs would be highly desirable. Remote indicating seals on key declared sample ports, and hydrogen fluoride detection to provide indication of the installation of new, undeclared ports may be appropriate. Cameras with change-detection software, or simple motion detectors, could be simple but effective tools. Neutron and photon detectors at feed and withdrawal stations and at key portals, even roving detectors, could be considered to detect illicit feed and withdrawal stations in a timely fashion. These technologies would provide added depth for a toolbox from which the IAEA could select, depending on the capacity and technology of the specific enrichment plant, the results of acquisition pathway analysis, the presence of a broader conclusion in the host state and the degree, if any, of international management and engagement.

We find that the IAEA has powerful deterrent tools in the form of short-notice limited frequency unannounced access activities, and, in extreme cases, the ability to call short-notice meetings of the Board of Governors.

Finally, while the analysis here has focused on GCEPs specifically under the provisions of the NPT verified by the IAEA, a future Fissile Material Cutoff Treaty, or a treaty requiring low (or zero) levels of fissile materials and nuclear weapons, will require similar safeguards at all GCEPs, including in currently nuclear-armed states, so the technologies and procedures discussed here need to be understood to be universally applicable.

Notes and references

1. Safeguards activities pursuant to the NPT at GCEPs in Member States of the European Atomic Energy Community (Euratom) are implemented by both the IAEA and Euratom under the IAEA-Euratom safeguards agreement (INFCIRC/193).
2. W. Bush et al., “Model Safeguards Approach for Gas Centrifuge Enrichment Plants,” Paper presented at the 2006 IAEA Symposium on International Safeguards, Vienna, Austria, 16–20 October, 2006.
3. The IAEA considers 25 kg of uranium-235 contained in HEU to be a significant quantity “for which the possibility of manufacturing a nuclear explosive device cannot be excluded.” See *IAEA Safeguards Glossary: 2001 Edition*, International Nuclear Verification Series No. 3, 23, Vienna: International Atomic Energy Agency, 2001, https://www.iaea.org/sites/default/files/iaea_safeguards_glossary.pdf
4. We consider weapons-grade uranium to be uranium enriched to 90% or greater in uranium-235 (by isotopic fraction). Nevertheless, all highly enriched uranium (defined as uranium enriched to greater than 20% in the uranium-235 isotope) can be considered weapons-usable. See U.S. Department of Energy, “Highly enriched uranium: striking a balance: a historical report on the United States highly enriched uranium production, acquisition, and utilization activities from 1945 through September 30, 1996,” Revision 1, 2001, http://fissilematerials.org/library/doe01.pdf.
5. IAEA Safeguards Glossary, 21.
6. L. Eric Smith, Alain R. Lebrun, Rocco Labella, “Potential Roles for Unattended Safeguards Instrumentation at Centrifuge Enrichment Plants,” *Journal of Nuclear Materials Management*, 42, no. 1 (2013): 38–58.
7. Patrick Migliorini, “Modeling and Simulation of Gas Centrifuge Cascades for Enhancing the Efficiency of IAEA Safeguards,” Ph.D. Dissertation, University of Virginia, 2013, and James Ely et al., “On-Line Enrichment monitor (OLEM): Supporting Safeguards at Enrichment Facilities,” 2014 Safeguards Symposium, International Atomic Energy Agency (2014). Given the cascade piping characteristics, and dimensions and operating parameters for the

centrifuges specified in Migliorini 2013, along with the operating pressure for cascade piping given in Ely 2014, it becomes apparent that the ratio of material in piping to material in centrifuges is quite small.

8. Alexander Glaser, "Characteristics of the Gas Centrifuge for Uranium Enrichment and Their Relevance for Nuclear Weapons Proliferation," *Science and Global Security*, 16, (2008): 1–25.
9. Karl Cohen, *The Theory of Isotope Separation as Applied to the Large-Scale Production of U-235* (New York: McGraw-Hill, 1951), 6.
10. B. Brigoli, "Cascade Theory," Ch. 2 in Stelio Villani, ed., *Uranium Enrichment* (Berlin: Springer-Verlag, 1979), 21.
11. For fixed $R^{product}/R^{feed} = 5.93$ in each set of cascades, four sets of cascades are required to achieve 90% enrichment by the stages: 0.72% to 4.1%, 4.1% to 20.3%, 20.3% to 60.3% and 60.3% to 90%. To achieve 90% enrichment in 3 stages requires $R^{product}/R^{feed} = 10.75$, which is appropriate for producing 7.2% enriched uranium from natural uranium.
12. P. Migliorini, "Modeling and Simulation of Gas Centrifuge Cascades," 40.
13. The criticality safe dimension for an infinite 90%-enriched uranium-235 slab is 3.8 cm. This is about an order of magnitude smaller than the 36.83 cm inner radius of a 30B product cylinder. Thus, a 0.8 cm-thick layer of 90%-enriched UF6 desublimated on the inner walls of a 30B cylinder would also be criticality safe. This corresponds to about 190 kg of UF6, which is about 8% of a 30B cylinder's 2277 kg maximum fill weight for LEU up to 5%-enriched material. The product cylinder fill rate for the misuse scenarios described in this paper is about 8% of that under normal operation. "Nuclear Material Safeguards For Uranium Enrichment Plants: Part 3–Uranium Enrichment Plant Description and Material Control and Accountability Procedures," ISPO-347/R8 Part 3, Oak Ridge National Laboratory, 2007, 5.62.
14. Mark M. Pickrell et al., "Detection of Illicit HEU (uranium-235) in a Fuel Cycle Enrichment Plant," Paper presented at the 47th Annual Meeting of the Institute of Nuclear Materials Management, Nashville, TN, 16—20 July 2006.
15. International Atomic Energy Agency, "The Structure and Content of Agreements Between the Agency and States Required in Connection with the Treaty on the Non-Proliferation of Nuclear Weapons," INFCIRC/153 (Corrected), 1972, paragraph 28.
16. Joerg H. Menzel, "Safeguards Approach for Gas Centrifuge Type Enrichment Plants," *Journal of Nuclear Materials Management*, 12, no. 4 (1983): 30—37.
17. L.E. Smith et al., "Potential Roles for Unattended Safeguards Instrumentation at Centrifuge Enrichment Plants."
18. L. Eric Smith et al., "Modeling and Analysis Methods for an On-Line Enrichment Monitor," *Journal of Nuclear Materials Management*, 44, no. 3 (2016): 27–44.
19. James Ely et al., "Enrichment Measurement with the On-Line Enrichment Monitor (OLEM)," Paper presented at the 57th Annual Meeting of the Institute of Nuclear Materials Management, Atlanta, GA, 24–28 July 2016.
20. Roy J.G. Veldhof et al., "Overview of Conducted Field Trials at URENCO," Paper presented at 2014 IAEA Symposium on International Safeguards, Vienna, Austria, 20–24 October 2014.
21. J.M. Whitaker, M. Laughter, and J. Howell, "Using Process Load Cell Information for the IAEA Safeguards at Enrichment Plants," IAEA-CN-184/116, Paper presented at the 2010 IAEA Symposium on International Safeguards, Vienna, Austria, 1–5 November 2010.
22. L.E. Smith et al., "Field Trial of an Unattended Verification Station for UF6 Cylinders," Paper presented at the 57th Annual Meeting of the Institute of Nuclear Materials Management, Atlanta, GA, 24–28 July 2016.

23. L.E. Smith et al., "Potential Roles for Unattended Safeguards Instrumentation at Centrifuge Enrichment Plants."
24. J. Michael Whitaker, "Uranium Enrichment Plant Characteristics–A Training Manual for the IAEA," ORNL/TM-2005/43, Oak Ridge National Laboratory, 2005. http://fissilematerials.org/library/ornl05a.pdf.
25. Jill N. Cooley et al., "Model Safeguards Approach and Innovative Techniques Implemented by the IAEA at Gas Centrifuge Enrichment Plants," Paper presented at the 48th Annual Meeting of the Institute of Nuclear Materials Management, Tuscon, AZ, 8–12 July 2007.
26. See, for example, "Hydrogen Fluoride Gas Laser Detection," Senscient, http://www.senscient.com/hydrogen_fluoride_detection.html.
27. M.M. Pickrell et al., "Detection of Illicit HEU (uranium-235) in a Fuel Cycle Enrichment Plant."