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Timely Verification at Large-scale Gas Centrifuge Enrichment Plants

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Timely Verification at Large-scale Gas Centrifuge Enrichment Plants

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Abstract
Commercial-scale gas centrifuge enrichment plants present a substantial challenge to the goal of timely detection and deterrence of the production of weapons-grade uranium. If one 500 tSWU/year unit of a reference 4000 tSWU/year enrichment plant were appropriately reconfigured, the plant could produce 17 SQ of weapons-usable material per month, assuming the use of ten days prior production of 5% enriched LEU, plus ongoing production in the remaining unmodified units. A toolbox of unattended verification technologies, however, could be used to detect this activity quickly, motivating the IAEA to initiate follow-up activities, potentially on a rapid time scale. These unattended measurement devices should be implemented only as needed, and must have extraordinarily low false alarm rates. They could potentially provide significant benefit to plant operators, in particular through allowing the release of LEU product cylinders without the physical presence of inspectors.

1. Introduction

In an idealized calculation, the production of one Significant Quantity (SQ) of weapons-grade HEU[1] starting from 8t of natural uranium requires approximately 5 tSWUs. Starting from 0.6 tonnes of 5% enriched uranium, it requires only 1.2 tSWUs. A single commercial 4000 tSWU/year plant, capable of fueling about 30 1 GW(e) nuclear reactors, could then, *in this highly idealized calculation*, produce about 9 SQ of weapons-grade HEU per day, until it had consumed its on-hand supply of 5% enriched uranium. One month's prior production of 5% enriched uranium would be about 45t, and 80 SQ could be produced in 9 days, using this supply. A similar calculation for a 500 tSWU/year plant yields 10 SQ in 9 days. Either of these highly idealized scenarios would present a very significant challenge for timely detection and deterrence of misuse of nuclear technology for the manufacture of nuclear explosive devices, the fundamental goal of IAEA safeguards. Below we examine more realistic scenarios for consideration, but they also present significant challenges.

Timeliness considerations are also important in the context of a Fissile Material Cutoff Treaty (FMCT), or a future treaty limiting the amount of military fissile material and of nuclear weapons to very low, or even zero, values. In particular, timely detection might become increasingly critical as military fissile stockpiles shrink.

Four sections follow in this paper. In Section 2 we examine, in a less idealized manner than above, sample misuse scenarios at a reference centrifuge enrichment plant. In Section 3 we outline a potential toolbox of unattended verification technologies that could be drawn from to provide timely detection and therefore deterrence against the scenario defined in Section 2 and related scenarios. In Section 4 we briefly examine the process of timely response to an alarm in the context of IAEA verification of the Treaty on the Non-

Proliferation of Nuclear Weapons (NPT), and in Section 5 we summarize and make recommendations.

2. Sample Scenarios

The IAEA is required to provide timely detection of the following scenarios at uranium enrichment facilities[2]:

1. Diversion of natural, depleted or low-enriched UF_6 from declared flow in a facility
2. Misuse of a facility to produce undeclared product from undeclared feed.
3. Misuse of a facility to produce UF_6 at enrichments higher than the declared maximum, in particular highly enriched uranium.

For our sample scenarios we consider cases where a gas centrifuge enrichment plant (GCEP) is used to produce large quantities of weapons-grade uranium as quickly as possible without detection, in a variant of the "abrupt diversion" scenario[3]. These scenarios are relevant to both the NPT and FMCT (and beyond). Since direct access to weapons-usable material is provided in these cases, arguably they put the greatest stress on the question of timeliness.

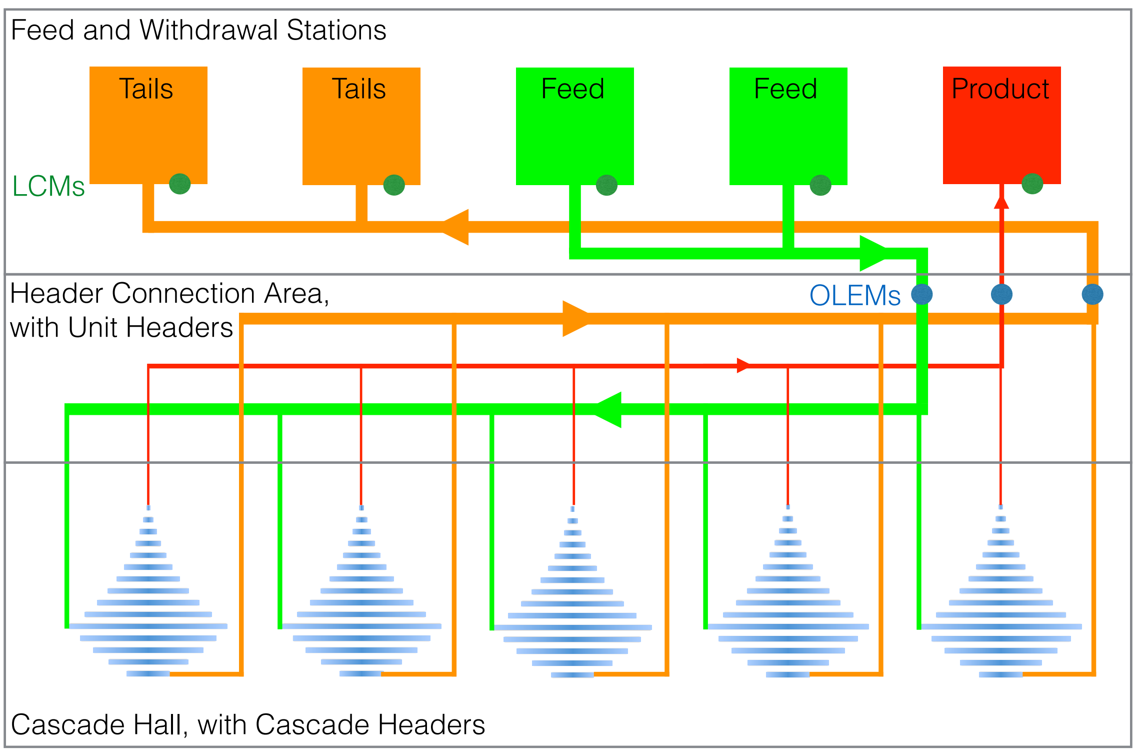

Figure 1: Simplified "plumbing diagram" for a single unit of a reference enrichment plant. Cascades per unit reduced from 10 to 5 for clarity. The number of feed and withdrawal stations is arbitrary. LCMs (Load Cell Monitors) and OLEMs (On-Line Enrichment Monitors) are discussed in Section 3.

In a 2013 article, Smith, Lebrun and Labella[4] introduce a "reference" centrifuge enrichment plant, with 4000 tSWU/year capacity. The reference plant is made up of eight "units," of which one is illustrated in Fig. 1, consisting of ten cascades each (reduced to 5 for clarity in the figure). 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 500 tSWU/year of enrichment capacity, while each cascade has 50 tSWU/year capacity. For round numbers we will assume that each centrifuge has a nominal 50 kgSWU/year capacity, and thus each cascade is made up of 1000 centrifuges. We assume here, again for round numbers, that these centrifuges operate with gain $R_p/R_f = R_f/R_t = 1.2$, allowing them to enrich from 0.71% ^{235}U to 5.05% in eleven stages under normal operating conditions. Assuming four stages of these same centrifuges on the stripping side, the tails are produced with a reasonable enrichment value of 0.29%. In order to estimate the equilibration time of our cascades, we will assume, once again for round numbers, that each centrifuge contains 10g of uranium, with an equal amount of uranium resident in the piping associated with each centrifuge.

There are a number of potential approaches to misusing an enrichment plant to produce weapons-grade uranium.[5] In our sample scenarios we will assume that the operator chooses to maintain the integrity of the individual cascades and to place them into a new series-parallel configuration. For simplicity and scalability, and to avoid long interconnections, we will further assume that the operator maintains the integrity of the individual large-scale units.

The operator confronts a problem that the higher cascades in a linked "cascade of cascades" composed of cascades designed for enrichment from natural uranium to 5% are incorrectly shaped for their tasks. Ideal cascades (those with no mixing of flows at different enrichment levels) designed for operation at higher enrichment would have a more "blunt" shape. We do not consider here either reshaping cascades by rearranging centrifuges to avoid mixing and so preserve the total SWU capacity, nor do we consider taking centrifuges out of service to "sculpt" ideally shaped upper cascades from ones configured to be ideal for lower enrichment. Instead we allow for non-ideal operation of the upper cascades, which reduces their SWU capacity due to mixing at each stage within the cascade, but preserves the UF_6 flow in every stage and centrifuge. Interestingly, such a non-ideal cascade, while losing SWUs due to mixing, gains in enrichment. Said simply, the sharper shape of the enrichment side of the low-enrichment cascade is "pickier" about the uranium that it allows to exit, so the product enrichment is higher. We find, then, three classes of cascades.

Table 1: Classes of Cascades in Abrupt Diversion Scenario

	Feed Enrichment	Product Enrichment	Tails Enrichment	tSWUs/year
Original	0.71%	5.05%	0.29%	50
Mid Group	5.05%	33.6%	2.26%	49.5
Top	33.6%	94.0%	27.7%	28.7

A question arises as to what the operator would do with the tails from the upper cascades. Problematically, 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 the prior 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 would be captured and not recycled into the system. This approach is inefficient in

SWUs and in use of uranium, so significantly reduces the potential rate of production of weapons-grade HEU, and even more significantly the total amount that can be produced from a given amount of pre-enriched LEU. It is, however, expeditious and simple.

The ratio of feed to product in these cascades is uniformly 11.2. Thus a single ten-cascade unit could be reconfigured to have nine Mid Group cascades feeding a single Top cascade, with some capacity to spare in the Top cascade. This also means that the remaining seven units could feed the reconfigured unit steadily, so long as they themselves were fed with natural UF_6. The final unit would have some capacity to spare.

Once the cascades are reconfigured, the next key step is to bring them to equilibrium at their new operating point. Figure 2 shows a calculation of the time evolution of their enrichment levels. Evidently equilibration happens quite rapidly (with the assumed inventory of U per centrifuge), likely requiring quite a bit less time than would be needed for the reconfiguration of inter-cascade piping and installation of new feed and withdrawal stations.

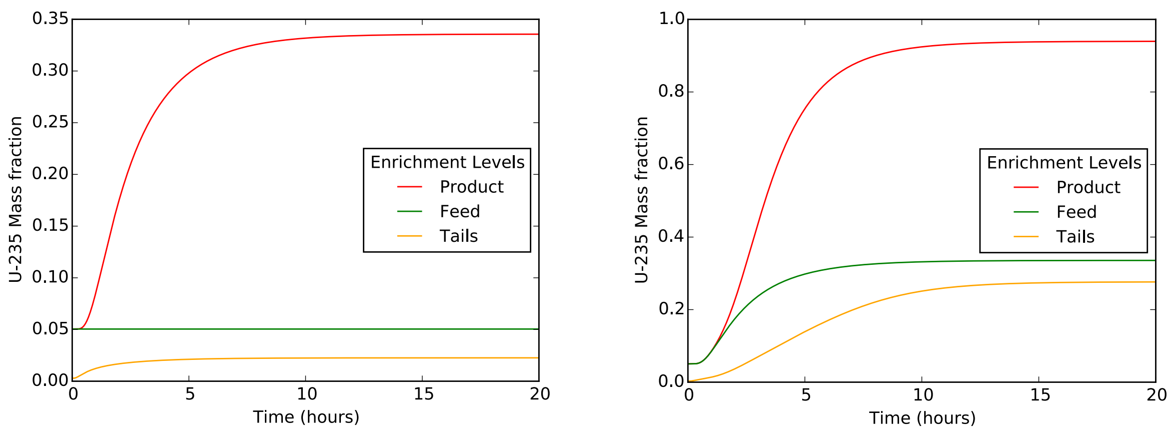

Figure 2: Time evolution of product, feed and tails concentrations of the two new classes of cascades.

What scenarios can the enrichment plant pursue once the newly reconfigured cascades have been equilibrated? A nominally 500 tSWU/year plant composed of a single unit, with 1 month's production of 5% enriched U on hand, can produce about 1.7 SQ of weapons-grade material in 3 days of enrichment, before running out of enriched feedstock. Both the amount that can be produced, and the production time, vary linearly with respect to the pre-existing stockpile, making this a very important factor. A 4000 tSWU/year plant fully reconfigured to make weapons-grade HEU could produce 13 SQ in 3 days of enrichment, starting from a 1-month stockpile of material. The size of the stockpile again is an important factor. However, a 4000 tSWU/year plant, with one 500 tSWUs/year unit producing weapons-grade material, while continuing to produce 5% enriched feedstock with 7/8 of the plant, can produce 12 SQ per month for as long as the plant is supplied with 0.71% enriched UF_6. If 10 days stored production of 5% LEU from seven units is available, plus the continuing production from these seven units, it could produce 17 SQ per month.

These numbers correspond to significant reductions from the idealized calculation presented in the introduction, about a factor of 2 reduction in the SQ production rate, and a factor of 6 reduction in the total SQ's produced from a given stockpile of 5% enriched LEU. In each case, furthermore, one also needs to add the time required for reconfiguration and equilibration. Nonetheless, these results still constitute a significant challenge for timely verification.

It should be stressed that these sample scenarios, while more useful than the idealized calculations presented in the introduction, are no more than a guide to some of the major factors that need to be considered, and provide only a qualitative sense of the timeliness issues at hand.

3. Toolbox of Verification Technologies

The objective of IAEA Comprehensive Safeguards Agreements is defined[6] 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." In this section we outline a toolbox of potential unattended verification technologies that could be implemented to provide timely detection and therefore deterrence against the scenarios defined in Section 2 and related scenarios. The implementation of a subset of such systems would need to be undertaken on the basis of a graded approach, depending on the capacity and technology of the specific enrichment plant, the results of Acquisition Pathway Analysis, and the presence of a Broader Conclusion that all nuclear material in the host state has remained in peaceful activities, as well as 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. In principle, product cylinders may be able to be released without delay for human inspection.

Smith, Lebrun and Labella[4] propose three main 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). Here we briefly describe these technologies, and their relevance to our sample scenario.

<u>OLEM:</u> On-Line Enrichment Monitoring systems[7], shown in figure 4, are to be non-intrusively attached to *unit*, not *cascade*, headers, as shown in figure 1. They are proposed to be attached to the product, feed and tails headers of each unit, so the reference GCEP discussed in Section 2 would be equipped with 24 such systems. By use of photon emission measurements, with appropriate calibration for removing the effects of pipe deposits, these systems can determine to a few percent accuracy the density of ^{235}U in the gas flowing through the unit header. By use of 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 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 beginning to be deployed.

LCM: 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 Fig. 1. This would be an intrinsically shared measurement with the operator. LCM measurements, combined with OLEM measurements, would allow near real-time closure of both the total mass balance and ^{235}U 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.

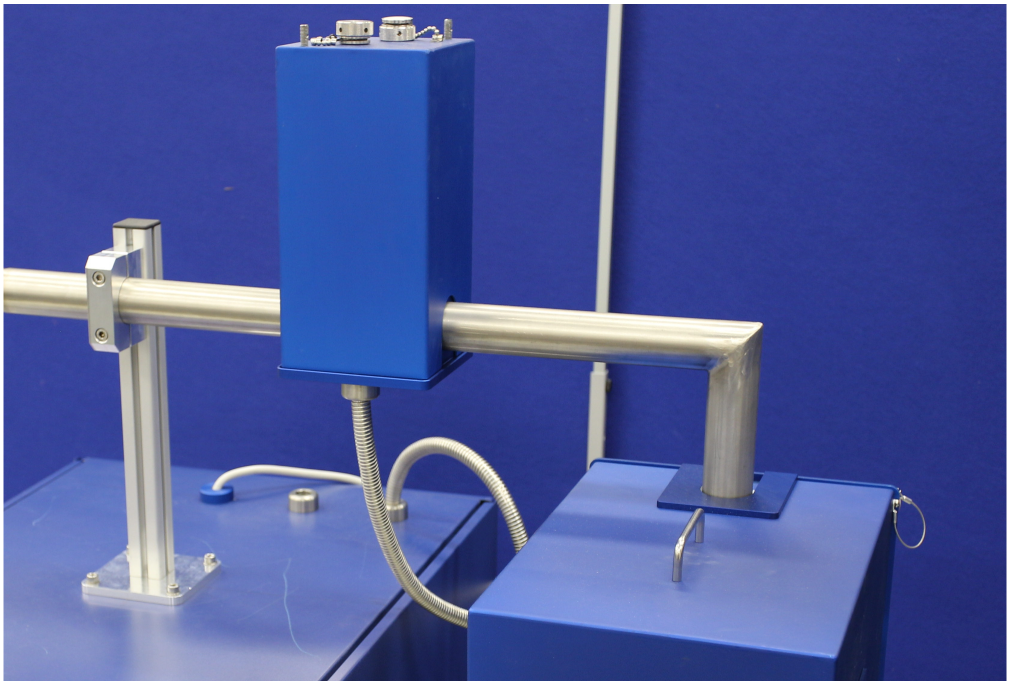

Figure 3. On-Line Enrichment Monitor. A γ detector (bottom right) measures the density of ^{235}U while sensors (middle, bottom right) measure pressure and temperature in unit header pipes[8].

UCVS: Unattended Cylinder Verification Stations would measure the total uranium in feed cylinders arriving at a GCEP, as well as uranium in product and tails cylinders ready to be shipped out of a GCEP. UCVS mass measurements could be used to independently verify data from accountancy scales shared by the operator with the IAEA. In addition, UCVS would measure the amount of ^{235}U contained in cylinders via neutron singles and doubles count rates, driven by the proxy of naturally occurring ^{234}U that is enriched along with ^{235}U. ^{234}U undergoes alpha decay, and through an (α,n) reaction on fluorine produces ~ 1 MeV neutrons. UCVS would give assurance that all of the material that passes through the unit headers, and is perhaps even mixed into final product cylinders, is indeed sent out of the plant to the expected recipient. The technologies that can be used for UCVS are under development and qualification.

Smith, Lebrun and Labella[4] argue that OLEM, LCM and UCVS together would provide much improved effectiveness of safeguards, by monitoring both total and ^{235}U mass balances in near real time, and assuring with high accuracy that all enriched material produced in a large GCEP is directed to its declared, peaceful use. These unattended technologies would also provide improved efficiency, in particular 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, as a consequence, provide the added non-proliferation benefits of reducing the normal on-site inventory of enriched UF_6 and, in conjunction with appropriate containment and surveillance, providing the IAEA with better knowledge of this inventory.

In principle this suite of technologies would detect the scenarios outlined in Section 2, and related scenarios, because the mass flow in the headers for at least one unit would necessarily be shut down. However this detection depends crucially on the Load Cell Monitors, which are not under the full control of the IAEA, and thus do not constitute fully independent measurement sources.

Unit Header Flow Monitors: We suggest that methods for measuring the flow speed of UF_6 at the location of the OLEMs should be developed. The possibilities range from non-intrusive but complex, such as using a pulsed neutron source to drive fission and detecting the delayed arrival of fission products downstream[9], to intrusive but simple, such as installing a differential pressure measurement device across a restriction in the header pipe[10]. A number of technologies between these two extremes could be envisioned. The combination of OLEMs plus reliable unit header flow measurements, both under IAEA seal, would constitute a very powerful verification tool.

In our scenarios, however, all of the above safeguards could be circumvented if the operator were simply to inform the IAEA that one or more units were being taken off line for maintenance. If this happens 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 a Limited Frequency Unannounced Access (LFUA) to the relevant cascade hall in order to confirm that no reconfiguration was underway. Thus it would be very desirable for the IAEA to have unattended means to detect quickly significant reconfiguration, 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 a particular enrichment plant.

Unattended Detection of Potential Reconfiguration: Through the Design Information Questionnaire and Design Information Verifications, the IAEA should be informed of, and verify, the presence off all sample ports installed in a centrifuge hall 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, such as identified in Section 2. It may be possible to install remote tamper-indicating seals on critical ports, and obligate the operator to inform the IAEA when it planned to use such ports. If an unusual number of these critical ports were accessed during a period when the associated unit was said to be offline, this could be an additional factor for the IAEA to consider in deciding to request a LFUA.

Cascades can also be reconfigured through the installation of new ports. Inevitably this process would result in releases of uranium hexafluoride, UF_6, which rapidly reacts with atmospheric water vapor forming uranyl fluoride, UO_2F_2, particulate matter and hydrogen fluoride, HF, gas. At the initial reconfiguration, when the IAEA should catch this activity in order 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 much more easily and quickly detected, and less easily contained than locally deposited uranyl fluoride particles. Commercial Open Air Gas Detection systems based on eye-safe lasers can sample path lengths above 100m. Some study would be required to optimize a system, 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 an LFUA.

If the piping to a cascade is reconfigured, in general the activity should be visible. Cameras could be located strategically, or could be moved, or mirrors moved, 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 the procedure currently used by inspectors during cascade hall access, where visual inspection is compared against photo albums of the verified configuration. Again it would be important to confirm an extremely low false alarm rate, as well as high reliability of detection.

<u>Detection of Illicit Feed and Withdrawal Cylinders:</u> As part of the reconfiguration required for the scenarios of Section 2 and related scenarios, it would be necessary to locate new feed and withdrawal cylinders in, or connected to, a cascade hall or header connection area. While it is challenging to measure neutrons from centrifuges[11], due to the low inventory of ^{234}U, cylinders containing kilograms of highly-enriched UF_6 produce neutrons at high rates. During LFUA activities inspectors could carry neutron detectors to detect hidden feed and withdrawal cylinders. More speculatively, robots could be programmed to "rove" through the relevant regions of enrichment plants carrying neutron detectors. Alternatively these robots could be configured to travel on rails above areas where illicit cylinders might be located. If such a robot either detected a large source of neutrons in an unexpected location, or was prevented from entering a normally accessible area, the robot could signal this situation, again providing significant motivation for the IAEA to call a LFUA.

<u>Timely Data Transmission:</u> 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 instrument discussed here indicating state-of-health and "nominal operation" or "human verification required," perhaps every 6 hours, might be sufficient. Along with the choice of technologies from the proposed toolbox, this frequency of data transmission should be

graded depending on the capacity and technology of the specific enrichment plant, the results of Acquisition Pathway Analysis, and the presence of a Broader Conclusion in the host state, as well as the degree, if any, of international management and engagement.

4. Timely Response by IAEA

The IAEA has at its disposal two powerful tools for timely response. The first is the Limited Frequency Unannounced Access (LFUA). As detailed in the approach of the Hexapartite Safeguards Project for GCEP safeguards, this gives the IAEA inspectors, on two-hours notice, access to cascade halls at enrichment plants. As discussed above, if the IAEA were to detect something amiss through multiple independent signals, it would be justified in calling for a short-notice LFUA. Since there will likely not be many large GCEPs constructed in the near future, designated inspectors could be stationed so as to be able to arrive promptly. The capacity and technology of the specific enrichment plant, the results of Acquisition Pathway Analysis, and the presence of a Broader Conclusion in the host state, as well as the degree, if any, of international management and engagement should be taken into account by the IAEA in deciding on the urgency of requesting 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, after an LFUA was called, inspectors were either prevented from entering a plant or found evidence of significant misuse when they did enter, they would report to the IAEA this substantial anomaly. Presumably the Department of Safeguards would attempt to resolve the situation on a technical basis at an appropriate management level, informing the IAEA Director General as appropriate. If necessary the Director General would 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 would function as a powerful deterrent.

5. 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 a naïve SWU calculation would suggest. However these step could be perhaps be accomplished in days, and the subsequent production rate could be large. Fortunately On-Line Enrichment Monitors are now being deployed, and other technologies are under development. There is also some time before it is likely that there will be an expansion of large GCEPs, so it should be possible to implement 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 to implement the depth required for timely decisions. In particular flow measurements under IAEA seal as a complement to OLEMs would be highly desirable. Remote indicating seals on key declared sample ports, and hydrogen fluoride detection to provide notice of the installation of new, undeclared ports may be needed. Cameras with change-detection software, and even potentially robots measuring neutron emission to detect illicit feed and withdrawal stations could 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, and the presence of a Broader Conclusion in the host state, as well as 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 Inspections, 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 levels of fissile materials and nuclear weapons, or even zero, 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.

Acknowledgements
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