Volume XLIII, Number 4

JNMM Journal of Nuclear Materials Management

Advertising Contact
Patricia Sullivan
INMM, 111 Deer Lake Road, Suite 100
Deerfield, IL 60015 USA
Phone: +1-847-480-9573
Fax: +1-847-480-9282
Email: psullivan@inmm.org

JNMM (ISSN 0893-6188) is published four times a year by the Institute of Nuclear Materials Management Inc. The Institute of Nuclear Materials Management (INMM) is an international professional society dedicated to development and promulgation of practices for the safe, secure and effective stewardship of nuclear materials through the advancement of scientific knowledge, technical skills, policy dialogue, and enhancement of professional capabilities.

DIGITAL SUBSCRIPTION RATES: Annual (United States, Canada, and Mexico) $200 for individuals. Institutional subscriptions are $350 per year. Single copy of the proceedings of the Annual Meeting (United States and other countries) $200. Send subscription requests to *JNMM*, 111 Deer Lake Road, Suite 100, Deerfield, IL 60015 USA. Make checks payable to INMM.

DISTRIBUTION and delivery inquiries should be directed to *JNMM*, 111 Deer Lake Road, Suite 100, Deerfield, IL 60015 USA, or contact Amy Lydic at +1-847-480-9573; fax, +1-847-480-9282; or email, inmm@inmm.org.

JNMM Journal of Nuclear Materials Management

Topical Papers

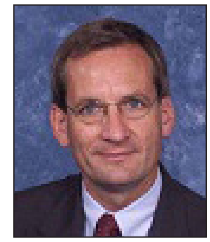
Institute News

Departments

Mission Statement

The INMM is an international professional society dedicated to development and promulgation of practices for the safe, secure and effective stewardship of nuclear materials through the advancement of scientific knowledge, technical skills, policy dialogue, and enhancement of professional capabilities.

Meetings, Workshops, and Relevancy



By Larry Satkowiak
INMM President

The last few months, many of us have been feverishly preparing for the INMM 56th Annual Meeting.

The "behind the scenes" activities of technical program committee, INMM headquarters, and the executive committee reminds me of the discordant sounds of the instruments warming up before a symphony: it all comes together in beautiful harmony when the curtain rises. That's a bit of an exaggeration, of course, but you get the point. As I write this column, we are undertaking a final review of the program, and quite honestly, it is impressive. From the opening to the closing plenary sessions, the quality of the abstracts, and breadth of topical areas, this program is phenomenal. On Monday, the opening plenary speaker is Ambassador Rafael Mariano Grossi speaking on *The Nuclear Equation: From Fukushima to Teheran and Beyond, Challenges and Opportunities.* Thursday's closing plenary is a panel focusing on utility of exercises for educational and training purposes with Carla Boyce, Federal Emergency Management Agency, Dan Johnson, World Institute for Nuclear Security and Rob Anderson, Royal Netherlands Embassy.

ESARDA and INMM

I had the pleasure of representing INMM at the European SAfeguards Research and Development Association (ESARDA) 37th Symposium, May 19–21, in Manchester, United Kingdom. I gave a plenary talk describing INMM and its ongoing relationship with ESARDA. INMM and ESARDA have worked together for many years, jointly sponsoring workshops since the 1990s. This effort was led by the INMM International Safeguards Technical Division (ISD) in particular, initially through the efforts of Cecil Sonnier and then later by Jim Larrimore, both former chairs of ISD. Their efforts are being continued by Michael Whitaker, the current chair. These workshops occur every three years with the location rotating between Europe, the United States, and Asia. The next installment of this joint workshop, the eighth in the series, will occur October 4–7, at the Jackson Lake Lodge in the beautiful Grand Teton National Park in Wyoming in the United States. The overall theme of the meeting is "Building International Capacity." The workshop will again feature four working groups: nuclear security, arms control, international safeguards, and education and training. Instead of the typical format where participants submit paper abstracts to be presented, this workshop will identify three specific discussion topics for each working group. Each participant is asked to develop a very short position statement on one or more topics in the working group of their choice. The call for position statements with a list of the topics for each working group has been posted on the INMM website.

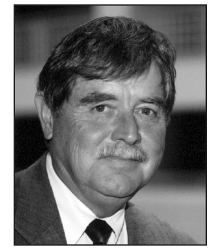
The professional relationship between ESARDA and the INMM was formalized somewhat a few years ago with the signing of a Letter of Intent to leverage our respective missions in a collaborative fashion.

Looking Forward

The Nuclear Security and Physical Protection Technical Division will hold the Vulnerability Assessment Tool Workshop, September 14-16, 2015, in Boston, Massachusetts, USA. As mentioned previously, the 8th INMM/ESARDA Joint Workshop, will be held October 4-7, at the Jackson Lake Lodge, Grand Teton National Park, Moran, Wyoming, USA. For more information check the INMM website at www.inmm.org.

Still Relevant After All These Years…

The Institute was formed in 1958, by a group of professionals—managers, scientists, and engineers who worked in the laboratories and facilities spawned by the Manhattan Project and later the Cold War. They shared a common concern regarding the proper management of nuclear materials with a primary focus on U.S. domestic issues. The thoughtfulness and forward thinking of our leaders over the last fifty-plus years formed the basis of what the INMM is today. Our membership is international in make-up (more than 40 percent of the abstracts submitted to the Annual Meeting were from the international community) and global in focus. Our members today address a number of issues ranging from policy to the highly technical, covering subjects such as nuclear security, nuclear terrorism, safeguards, detection enhancements, export control, arms control, nuclear trafficking, forensics, nuclear facility management, security issues, education/training, inventory controls, verification challenges, etc. To paraphrase song writer/singer Paul Simon, we are "still relevant after all these years…"



Providing Up-to-date Information

By Dennis Mangan
INMM Technical Editor

This issue of our Journal has five topical papers, one interesting book review, and our Industry News article, Taking the Long View in a Time of Great Uncertainty.

In his president's message, Larry Satkowiak writes briefly INMM 56th Annual Meeting. He also provides a nice summary of the European Safeguards Research and Development Association (ESARDA) 37th Symposium this past May. He notes that our Nuclear Security and Physical Protection Technical Division will hold a Vulnerability Assessment Tool Workshop this upcoming September. He concludes by also noting our Institute is "Still Relevant After All These Years…" It's an interesting reading.

The first topical paper is *Viability of UF_6 Cylinder Verification Using the Hybrid Enrichment Verification Array,* by L. Smith, David Jordan, Jon Kulisek, Ben McDonald, and Emily Mace, all of the Pacific Northwest National Laboratory in Richland, Washington, USA. They discuss the development of a Hybrid Enrichment Verification Array Method (HEVA) for International Atomic Energy Agency (IAEA) inspection needs. The second topical paper, *A Method for Assessing Safeguards Effectiveness and Its Application to State-Level Material Accountancy Verification* is by Jonathan Sanborn of JBS Consulting in Arlington, Virginia, USA. Sanborn likewise suggests a method for improving IAEA inspection needs. The third topical paper, *Expanding the Scope of Transparency to Strengthen the Nonproliferation Regime*, is authored by Jonas Segel from the Center for International and Security Studies at Maryland (CISSM), School of Public Policy, University of Maryland, College Park, Maryland, USA. In this paper, the author suggests ways of expanding transparency measures regarding exchange of nuclear material and weapon information as required by the Nuclear Nonproliferation Treaty. The fourth topical paper, *Safeguarding Uranium Production and Export – Conventional and Non-Conventional Resources* is authored by Craig Everton of the Australian Safeguards and Nonproliferation Office in Barton, Australia. He addresses the question of what are the appropriate level of controls at the start of the nuclear fuel cycle from both the perspective of IAEA safeguards and of national regulatory controls in this industry. The last topical paper, *Acquisition Path Analysis Quantified – Shaping the Success of the IAEA's State-Level Concept* is authored by Clemens Listner, Irmgard Niemeyer, and Morton Canty of Forschungszentrum Julich, Germany; Chantell Murphy from Los Alamos National Laboratory, Los Alamos, New Mexico USA; Gotthard Stein, Consultant, Bonn, Germany; and Arnold Rezniczek, UBA GmbH, Herzogenrath, Germany. This paper presents a methodology to accomplish the development of a customized safeguards approach for an individual state for the IAEA's state-level approach. The methodology is based upon network modeling, network analysis and strategic assessment.

Book Review Editor Mark Maiello provides an excellent and interesting review of *North Korean Nuclear Operationality*, a book edited by Gregory J. Moore.

In the *Taking the Long View in a Time of Great Uncertainty* column, Industry News Editor Jack Jekowski, who also serves as chair of the INMM Strategic Planning Committee, addresses Going Back to Our Roots--DOE's Nuclear Security Role, a very interesting article to read.

Should you have questions or comments, please feel free to contact me.

JNMM Technical Editor may be reached at dennismangan@comcast.net.

Viability of UF_6 Cylinder Verification using the Hybrid Enrichment Verification Array

L. Eric Smith, David V. Jordan, Jon Kulisek, Ben McDonald, and Emily K. Mace
Pacific Northwest National Laboratory, Richland, Washington USA

Abstract

In recent years, the International Atomic Energy Agency (IAEA) has pursued innovative techniques and an integrated suite of safeguards measures to address the verification challenges posed by advanced centrifuge technologies and the growth in separative work unit capacity at modern centrifuge enrichment plants. These measures would include permanently installed, unattended instruments capable of performing the routine and repetitive measurements previously performed by inspectors. Among the unattended instruments currently being explored by the IAEA is an Unattended Cylinder Verification Station (UCVS) that could provide independent verification of the declared relative enrichment, ^{235}U mass and total uranium mass of 100 percent of the declared cylinders moving through the plant, as well as the application and verification of a "Non-destructive Assay Fingerprint" to preserve verification knowledge on the contents of each cylinder throughout its life in the facility. As IAEA's vision for a UCVS has evolved, Pacific Northwest National Laboratory (PNNL) has been developing the Hybrid Enrichment Verification Array (HEVA) method as a candidate nondestructive assay method for inclusion in the UCVS. HEVA utilizes an array of sodium iodide spectrometers (NaI(Tl)) to simultaneously measure the direct gamma-ray signature from ^{235}U and via high-energy gamma rays induced by neutrons in specially designed collimators and the sodium iodide, the total neutron emission rate from the cylinder. Modeling and multiple field campaigns have indicated that HEVA is capable of assaying relative cylinder enrichment with a precision comparable to or perhaps better than today's high-resolution handheld devices, without the need for manual wall-thickness corrections. In addition, the HEVA method interrogates the full volume of the cylinder, thereby offering the IAEA a new capability to assay the absolute ^{235}U mass in the cylinder, and much-improved sensitivity to substituted or removed material. By hybridizing the two complementary radiation signatures, HEVA is also capable of detecting off-normal $^{234}U/^{235}U$ ratios, or ^{232}U that would indicate the presence of UF_6 material with non-natural origins. This paper describes HEVA signatures and analysis methods, a notional UCVS design based on HEVA detector modules, and preliminary HEVA viability findings in the context of IAEA's preliminary UCVS performance targets. Unresolved technical and implementation questions, and the path forward, are also discussed.

Introduction

The IAEA's model safeguards approach for gas centrifuge enrichment plants[1] describes the challenges associated with safeguarding large centrifuge enrichment plants and defines the high-level verification objectives for enrichment plant safeguards approaches, i.e., the timely detection and deterrence of: diversion of UF_6 from the declared flow; production of undeclared product at normal product enrichment levels from undeclared feed; production of UF_6 at enrichments higher than the declared maximum.

At present, the IAEA's safeguards approaches at enrichment plants are based on a combination of routine and random inspections, during which time a number of verification activities are performed, including: environmental sampling for subsequent laboratory analysis, collection of UF_6 samples from in-process material and selected cylinders for subsequent destructive analysis in a laboratory, and weighing and nondestructive assay (NDA) of a subset of the plant's cylinder flow and inventory. The weight measurements of cylinders are performed using either operator-owned scales or the IAEA's portable hanging load cells, while the NDA measurements utilize handheld gamma-ray spectrometers combined with ultrasonic wall-thickness gauges.

Detection of prominent diversion scenarios could be improved at enrichment plants if the IAEA could monitor 100 percent of material flows and periodically calculate independent uranium and ^{235}U mass balances for the facility. However, human and financial resources preclude continuous inspector presence at the facility to measure all of the material flow, using today's attended methods. Further, the portable measurement methods currently used by inspectors for cylinder verification have relatively low accuracy for the assay of relative ^{235}U enrichment, especially for natural and depleted UF_6, and no capability to assay the absolute mass of ^{235}U and total uranium in the cylinder, because of the highly localized nature of the instrument geometry and low-energy gamma-ray signature. The poor accuracy of today's cylinder verification instruments necessitates additional safeguards measures, including the destructive analysis of UF_6 samples from select cylinders. These are among the reasons that the IAEA is exploring how unattended instruments capable of continuously and more accurately verifying material flows (both in-process gas and cylinders) on a quasi-continuous basis could help improve the deterrence and timely detection of protracted diversion scenarios.[2,3,4,5]

One of the instrumentation concepts being considered by the IAEA is an Unattended Cylinder Verification Station (UCVS).[4,6] UCVS units could be located at key intersections of cylinder movement between material balance areas, or at the operator's accountancy scales (in order to take advantage of the facility's cylinder weighing operations). The station would include technologies for cylinder identification, NDA of the cylinder contents, video surveillance and data transmission to an on-site computer or inspectorate headquarters. UCVS units would be owned and operated by the IAEA, but the data streams could be shared with the operator (e.g., for process control) in conformance with IAEA requirements for shared-use instruments.

According to the IAEA, the NDA components of the UCVS will support several measurement objectives, including: unattended, independent assay of cylinder enrichment (E_{cyl}) and ^{235}U mass (M_{235}) for product, feed, and tail cylinders; independent assay of total uranium mass (M_U) as a confidence-building measure on the authenticity of data from operator weighing systems; and the unattended application, verification, and re-verification of an "NDA Fingerprint" to maintain the verification pedigree of the cylinder contents and to verify that no partial removal of material has occurred during the cylinder's life at the facility.[4]

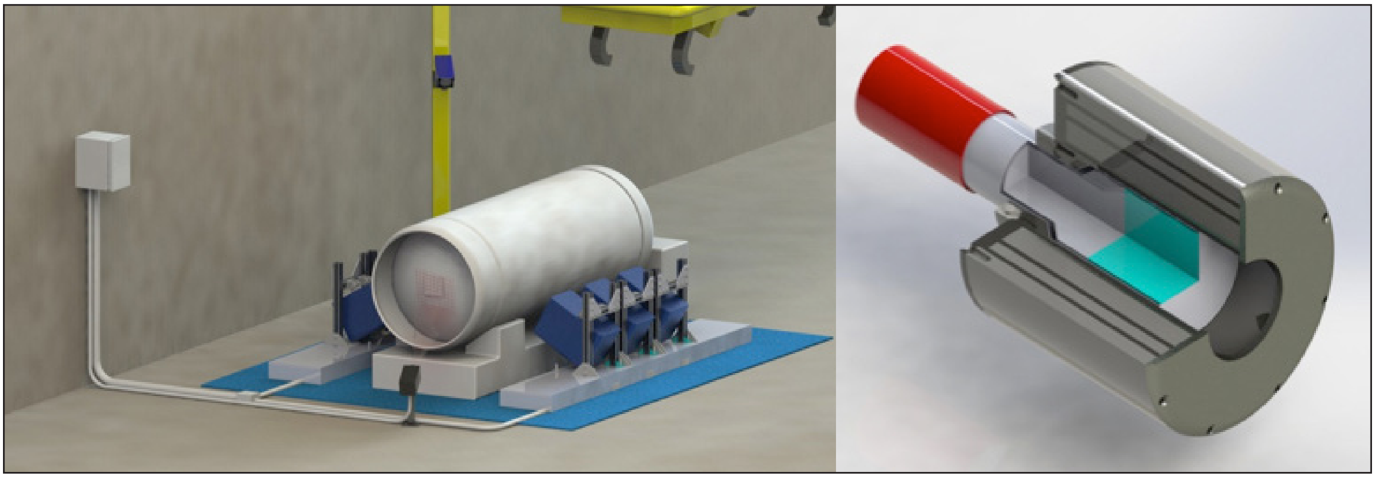
Though the potential of a UCVS system is understood, its field performance and operational viability in a commercial enrichment facility has yet to be fully tested. Under the auspices of the United States and European Commission Support Programs to the IAEA, a project has been undertaken to assess the technical and practical viability of the UCVS concept. The IAEA has issued preliminary functional requirements and performance targets to guide the viability study.[9] The IAEA has also identified two candidate NDA methods to be studied in the UCVS project, both of which were developed under support from the U.S. Department of Energy's (DOE) Next Generational Safeguards Initiative: the Hybrid Enrichment Verification Array (HEVA) being developed by Pacific Northwest National Laboratory (PNNL), and the Passive Neutron Enrichment Meter (PNEM) being developed by Los Alamos National Laboratory (LANL).[7,8]

PNNL's HEVA method is the focus of this paper. HEVA signatures and analysis methods, a notional UCVS design based on HEVA detector modules, and preliminary HEVA viability findings in the context of IAEA's preliminary UCVS performance targets are described. Unresolved technical and implementation questions, and the path forward, are also discussed.

The Hybrid Enrichment Verification Array Method: Overview

The HEVA field prototypes developed to date have consisted of three or four standard 7.6x7.6-cm NaI(Tl) detectors arrayed horizontally along one side wall of the UF_6 cylinder. Each detector is surrounded by a collimator with one or more sets of polyethylene and steel layers. The front of the collimator is covered with a thin (less than 0.5 cm thick) lead faceplate with a 7.6-cm diameter aperture. Details of various prototype designs can be found in References 10-13. Building on the modeling, analysis and field measurements performed to date for the HEVA method, along with IAEA guidance regarding the roles, requirements and performance targets for a UCVS instrument,[4,9] PNNL has developed a nominal conceptual design for a UCVS utilizing the HEVA method. This design should afford the flexibility for various deployment geometries and locations, for example cylinder flow patterns, the number of accountancy scales at the facility, and viable cylinder scanning geometries. It is assumed that the facility operator uses either cranes or trolleys to emplace and remove cylinders from the UCVS, and that this placement process allows for the permanent installation of radiation sensors near the surface of, but not in contact with, the cylinder side walls (Figure 1).

Figure 1. *Left:* Conceptual design of an unattended cylinder verification instrument based on the HEVA method. Three HEVA detector modules are deployed along each side of the cylinder, with mechanical supports that could accommodate Type 30B and Type 48 cylinders. An integrated UCVS would also include camera surveillance and cylinder identification technology. *Right:* HEVA shielding, specifically designed to convert emitted neutrons into high-energy gamma rays and to collimate the 186-keV signature.

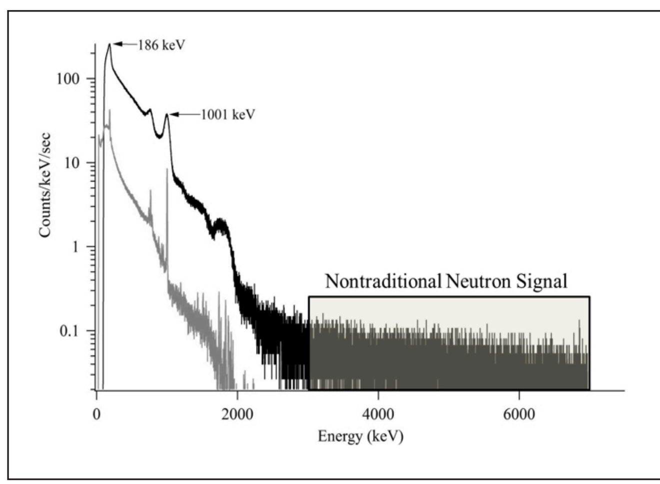


HEVA uses an array of NaI(Tl) spectrometers to simultaneously measure the 1) direct 186-keV signature from ^{235}U, and 2) total neutron yield via the high-energy gamma rays induced by uranium-origin neutrons in the iodine in the spectrometer crystal and in the ^{56}Fe of the spectrometer collimators (Figure 2). The "traditional" 186keV signature provides an unambiguous measure of E_{cyl}. Under assumptions of known $^{234}U/^{235}U$ behavior in the plant, the "non-traditional" total neutron signal can be calibrated to total M_{235} in the cylinder.[10,14,15] These signatures and corresponding analysis methods are described further here.

Traditional Enrichment Meter Method as Direct Measure of Ecyl

The traditional 186-keV emission from ^{235}U is the sole signature used by the IAEA in today's cylinder verification measurements with handheld spectrometers, and has been described extensively by others.[16,17] Systematic biases from variations in the cylinder wall thickness, cylinder wall deposit thickness/enrichment, and even UF_6 heterogeneity, can be problematic when measured with the small, highly localized (less than ~0.1 percent of the volume of a Type 30B cylinder, even less for a Type 48 cylinder), highly collimated gamma-ray spectrometers utilized by safeguards inspectorates today. Typical uncertainties achievable with handheld devices on product, feed and tail cylinders are known from IAEA's long history of verification measurements, and are reflected in the International Target Values for verification of UF_6 cylinders.[18]

Figure 2. Illustration of the traditional (186-keV) and nontraditional (nominally, the 3-8 MeV region corresponding to neutron-induced gamma rays) gamma-ray signatures utilized by the HEVA method (black). For comparison, the spectrum from a handheld high-purity germanium (11 percent relative efficiency) spectrometer similar to that used currently by the IAEA for cylinder verification is shown for the same product cylinder (grey).



Though the HEVA method collects the same 186-keV signature collected by the handheld spectrometers currently used by Euratom and IAEA, there are distinct differences in how these systematic variations, particularly the wall-thickness variations, are addressed, and their impact. In the case of the handheld devices, the collection area is very small (less than 100 cm^2) and typically located on the endcap, rather than the sidewall, of the cylinder. Measurements with a separate ultrasonic wall thickness gauge are used to correct the gamma-spectroscopy result, relative to the nominal endcap thickness for each cylinder type. In unattended HEVA assay, the collection area is much larger (e.g., four or more spectrometers, each having a field of view of several hundred square centimeters) and distributed along the length of cylinder side wall (on both sides in the nominal unattended system design).

The original hypothesis in early HEVA development was that this large-area, distributed measurement would "average out" any significant wall-thickness effects on the traditional 186-keV signature. In several field campaigns, some of which also collected ultrasonic wall-thickness data, this hypothesis has been supported: a calibration based on the aggregate 186-keV signal, summed over multiple NaI(Tl) spectrometers, can produce assay precision comparable to high-resolution hand-held devices.[10,12,13] A separate calibration is needed for Type 30B and Type 48 cylinders, due to the different nominal wall thickness for those cylinder types.

For HEVA's traditional 186-keV signature ($HEVA_T$), the key analysis challenge is the accurate extraction of the net peak area. This task is non-trivial for medium-resolution spectrometers for several reasons, but the shape and variation of the continuum underneath the 186-keV signal is primary. For example, down-scattered continuum from higher-energy lines (most notably, the 766-keV and 1001-keV lines present in the decay chain of ^{238}U) are not flat or even linearly varying with energy, but rather, exhibit significant curvature and complexity.

HEVA development efforts have sought nonproprietary algorithms that offer the potential for automated, unattended spectrum analysis. One spectroscopic analysis algorithm studied by PNNL involves the application of a discrete form of a so-called zero-area digital filter, the square-wave filter, to the pulse-height spectra collected with the NaI(Tl) spectrometers.[19,20] PNNL refers to the convolution of the original spectrum with the digital filter as the square wave convolute (SWC) spectrum. Previous HEVA experimental campaigns have studied the extent to which this simple proportionality can be exploited as the basis of an enrichment assay metric robust enough for systematic cylinder population variability (including wall thickness and differences in internal UF_6 configuration).[10,12,13]

More recently, PNNL has investigated window-based spectral analysis schemes and has drawn on previous work in the same application area. Walton et al.[16] applied a dual-window method to extract the continuum-subtracted 186-keV peak area in a medium-resolution spectrometer. The method relied upon a training, or calibration, set of UF_6 cylinder measurements to determine the best-fit values of the (linear) net peak-area model's coefficients. PNNL has developed a multi-window generalization of the Walton model, referred to herein as the multiple region of interest (multiple-ROI) approach. The multiple-ROI method enjoys the advantage (relative to the digital filter method) of greater robustness against systematic variations of the peak shape in the 186-keV region over a cylinder sample population. The price of this increased robustness is a corresponding reduction in statistical sensitivity to relatively small signal rates, because any window-based method requires the scaling and subtraction of relatively large ROI yields to extract a net peak area that is generally at least one order of magnitude smaller than these yields. Thus it would be expected that ROI-based methods will perform better for higher-enrichment cylinders, where the 186-keV signal is relatively intense, than for natural and depleted cylinders.

High-Energy Gamma-Ray Region as Indirect Measure of M_{235}

The use of total neutron count rate as a means of determining M_{235} is based on the production of neutrons in $^{19}F(\alpha,n)$ reactions, with the dominant alpha emitter being ^{234}U for all enrichments above natural.[14,16,21] The highly penetrating nature of this signature offers the potential for full-volume interrogation of the cylinder, and therefore, absolute measurement of uranium isotopic mass. Because this neutron signature is driven by ^{234}U, it is an indirect measure of M_{235} and its use requires knowledge of the $^{234}U/^{235}U$ ratio as a function of enrichment.

Studies by PNNL and others in recent years have improved the understanding of this neutron signature for cylinder assay, and its associated uncertainties, including the variation in the $^{234}U/^{235}U$ ratio in the natural uranium typically used as feed in commercial enrichment plants. Work by Richter et al.[22] analyzed mass spectrometry measurements of various uranium ore samples from around the world and set the limits of the natural variation. Another source of isotopic variation is that modern enrichment plants, depending on the price of uranium, may recycle tails as feed material, with potential impacts on the $^{234}U/^{235}U$ ratio in the product cylinders. Commercial enrichers may also use reactor-recycled uranium that typically has much higher $^{234}U/^{235}U$ ratios than material of natural origin. This challenge has been noted and studied by the authors in the context of unattended cylinder verification.[10,13] In HEVA development to date, it has been assumed that the typical feed of enrichment facilities under IAEA safeguards is of natural origin. Further, it has been assumed that a facility-specific calibration for NDA methods using the ^{234}U-derived signatures would incorporate knowledge about how the $^{234}U/^{235}U$ ratio changes as a function of enrichment in each unit/facility.

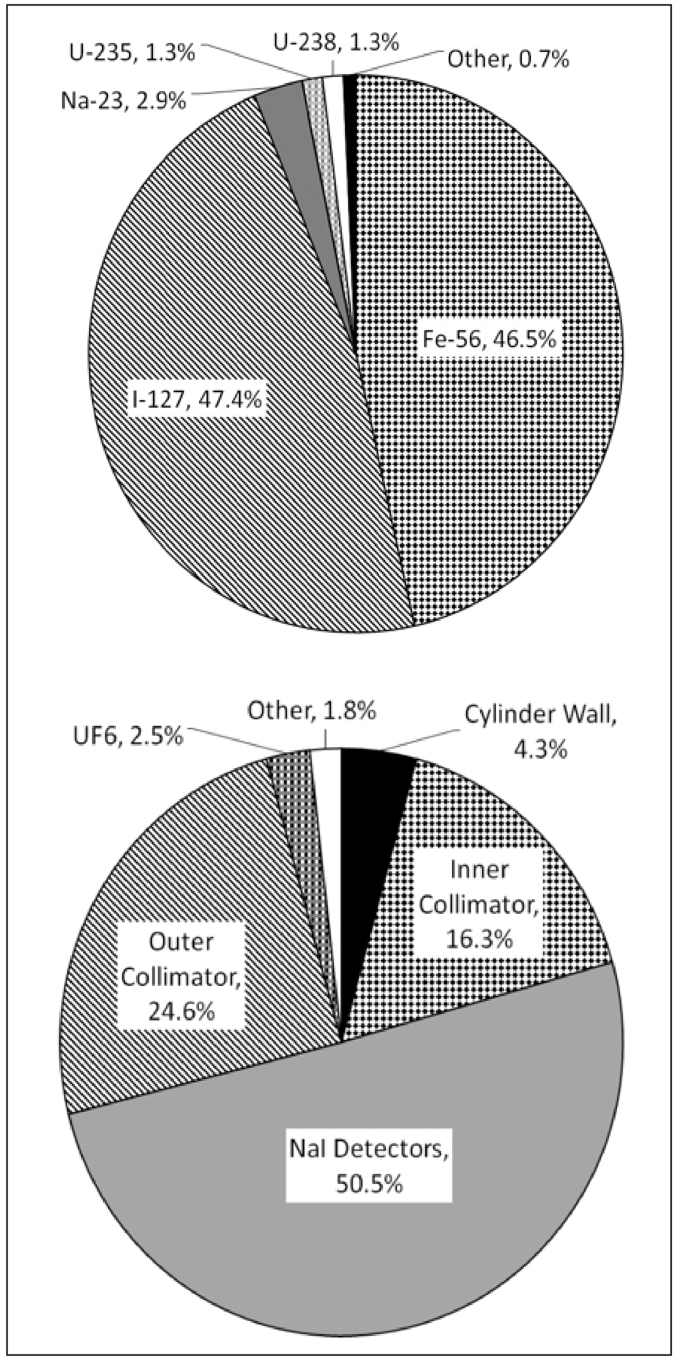
Another potential source of uncertainty in the neutron signature from cylinders is the geometric distribution of the UF_6 inside the cylinder, which can impact the magnitude and characteristics of the emitted neutron field and therefore, the detector response.[23] This topic is discussed in more detail later.

While others have studied the collection of neutron signals for cylinder assay, PNNL has pursued a novel, nontraditional signature for the same purpose. This approach is premised on the fact that neutrons produced in the UF_6 interact in the UF_6 itself and surrounding materials, and those interactions (e.g., inelastic scatter and neutron capture) induce high-energy gamma-ray signatures that extend to energies greater than 10 MeV (Figure 2). This nontraditional, high-energy gamma-ray signature is attractive because it allows exploitation of a neutron signature without the need for dedicated neutron sensors, yet preserves the important capability to interrogate the full cylinder volume (due to penetrability of the source neutrons).

In practice, PNNL has defined the nontraditional total neutron signature, $HEVA_{NT}$, to be the summation of gamma-ray counts in the 3-8 MeV range, and that signal can be summed across all of the NaI(Tl) spectrometers in the system. In contrast to the spectrum analysis in the 186-keV region, the count summation in the nontraditional case is relatively straightforward. Definition of the 3-8 MeV energy window channels requires an accurate energy calibration, which is currently determined by analysis of the positions of the 186-keV, 766-keV, and 1001-keV peaks.

PNNL investigations have shown that there are multiple sources for the high-energy gamma rays in the nontraditional neutron signal, with some of the most prominent signals coming from interactions with the iodine in the spectrometer crystals, and the 7.631-MeV and 7.645-MeV lines from neutron capture reactions on ^{56}Fe in the steel of the specially designed collimators. Tabulations of the relative contributions to the nontraditional signature are given in Figure 3, by isotope and also by hardware component.

Figure 3. Contributions to HEVA's non-traditional signature, tabulated by isotope (top) and hardware component (bottom)



An important finding of this study is that the vast majority (i.e., more than 90 percent) of the nontraditional neutron signal is generated by materials in the HEVA design that would be controlled by the IAEA (rather than nearby structures controlled by the operator). The remainder is primarily from the cylinder itself, either the contents or the steel vessel. This finding is important in terms of potential spoofing scenarios, where neutron converters might be intentionally placed or removed from the vicinity of the UCVS, thereby perturbing the calibration and/or collection of the nontraditional signature.

Note that Figure 3 is based on modeling of a specific HEVA field prototype design and a product cylinder at 3wt percent ^{235}U. The relative contributions would change slightly for other HEVA design configurations and cylinder enrichments.

In field campaigns to date, a population of typical cylinders from the facility has been used to define the calibration relationship between the magnitude of the nontraditional signal and the declared total ^{235}U mass in a cylinder. The PNNL team has proposed, however, that the facility-specific calibration might be defined instead by the IAEA's archival data of uranium isotopic ratios from destructive analysis on UF_6 samples drawn from the process or cylinders, and/or from environmental sampling at each specific facility,[24,25] thereby improving the level of independence of UCVS assay values.

Hybrid Methods as Direct Measure of E_{cyl}

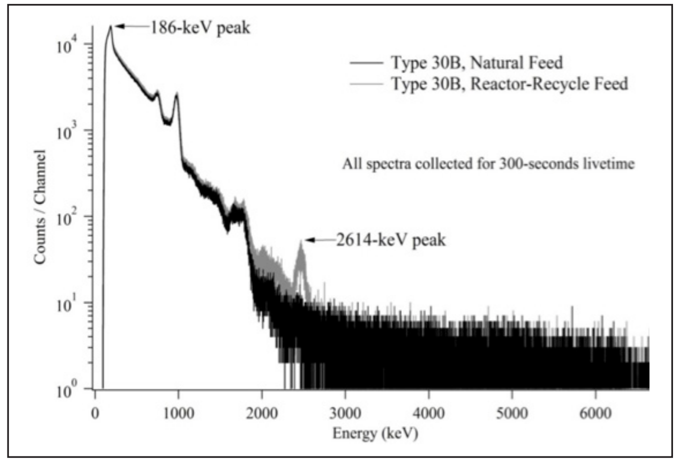
Previous statistical analysis by PNNL, using cylinders measured in various field trials, demonstrated that the nontraditional (neutron) and traditional (186-keV) signatures are only weakly correlated, indicating that combining the two signatures will produce more precise values for E_{cyl} than either signature acting independently.[10,12-14,26] To date, this hybrid analysis has consisted of a simple averaging (i.e., even weighting) of the traditional and nontraditional signatures, though other weighting schemes may ultimately prove advantageous.

It is important to recognize that applying the hybrid method for calculating relative enrichment, $HEVA_{Hybrid}$, requires knowledge of the total uranium mass in the cylinder, in order to translate the assayed value for M_{235} (from the nontraditional neutron signature) into a relative enrichment. In past analyses, and in this report, the operator's declared uranium mass value is used for this translation. This means that the hybrid assay method has lost some degree of independence in terms of verification. Completely independent methods for implementing a hybrid method have been postulated by PNNL, but not tested.

Hybrid Methods to Detect Off-Normal Cylinder Characteristics

The hybrid analysis method employed by HEVA offers the potential to flag inconsistencies between the enrichment predicted by the full-volume nontraditional signature and the direct ^{235}U traditional signature, and therefore to detect a $^{234}U/^{235}U$ ratio in a cylinder that is outside the typical range. PNNL has preliminarily explored an analysis approach for identifying atypical cylinders in a field campaign at an enrichment plant.[13] In that study, a deviation of 3σ was defined as the threshold to raise an anomaly flag, where σ is the uncertainty of the relative enrichment assays performed by that particular instrument in that particular facility, for the typical cylinders processed at that facility. If the $HEVA_T$ value of E_{cyl} based on the traditional ^{235}U signature is more than 3σ different from the $HEVA_{NT}$ value based on the nontraditional full-volume signature, a flag is noted for that cylinder.

Figure 4. HEVA spectra for a Type 30B product cylinder derived from natural feed (black), and a product cylinder of similar enrichment that originates from reactor-recycle feed material (grey). The presence of the 2614-keV peak is a clear indicator of non-natural UF_6 material.



In addition to the ^{234}U flag, HEVA spectra can also detect UF_6 of non-natural origin using the 2614keV peak (Figure 4). This peak is indicative of the presence of feed, product, or tails based on reactor-recycle uranium and, therefore, could be useful to safeguards inspectorates in the cylinder verification process. This signature could be quite weak, however, in very fresh product and tail material, as it depends on the grow-in of the ^{232}U daughters.

The full-energy gamma-ray spectra acquired at multiple locations along a cylinder contains a significant amount of information concerning the isotopics, age and origins of the cylinder contents. PNNL is exploring how this information can be exploited in support for the NDA Fingerprint concept. For example, changes in the UF_6 geometry or isotopic content (e.g., from substitution of material) should create significant perturbations in not only the key peak regions but also the continuum regions. A consistency check (e.g., using a chi-squared test) on successive HEVA spectra from that same cylinder location has the potential to provide sensitive detection of diversion scenarios.

Multiple Signatures for Indirect Measurement of M_U

The ability to independently determine three different parameters was discussed above: E_{cyl}; M_{234}, the mass of the ^{234}U in the cylinder (via the total neutron signature); and $R_{234\_U}(E_{cyl})$, the expected behavior in the $^{234}U/^{235}U$ and $^{234}U/^{238}U$ ratios as a function of enrichment in a specific facility. PNNL proposes that by using this combination of measured parameters, it is also possible to independently calculate the total mass of uranium in each cylinder where $M_U \propto M_{234} / (R_{234\_U}(E_{cyl}))$, where $R_{234\_U}(E_{cyl})$ is based on the IAEA's archive of environmental sample analysis and/or bulk sample analysis for that specific facility. A key characteristic of a total uranium mass calculated using these signatures is independence—no operator-declared information is needed to verify the declared net weight from scale data (either load cells or accountancy scales) shared from the operator. The absolute value of M_U, and its repeatability over multiple cylinder measurements, could offer a new and novel confidence-building measure for the authenticity of the shared data from operator weighing systems about each cylinder.[4]

Viability Findings

Uncertainty Budget Analysis

Understanding the sources and nature of uncertainties in HEVA measurements is important to assessing the viability of the method for meeting IAEA's objectives, and to guiding the continuing refinement of the method. In Reference 4, the IAEA highlighted the need for an uncertainty budget analysis for candidate unattended instruments; the IAEA provided an example of such analysis for the On-Line Enrichment Meter instrument in Reference 5. Here, a preliminary uncertainty budget analysis study for the HEVA method is described.

The total uncertainty of measured quantities such as E_{cyl}, M_{235}, M_U and the NDA Fingerprint can be broken down into several components:

- σ_{stat} is the random statistical uncertainty of the signatures measured by HEVA, for example in the net count rate under the 186-keV gamma-ray peak, or in the net nontraditional neutron count rate;
- σ_{sys_ran} is the random systematic uncertainty of the measured signatures. Random systematic uncertainties might include wall-thickness variations, cylinder age, material distribution in the cylinder, ambient background changes (e.g., nearby cylinder movements), instrument drift (e.g., gamma-spectrometer gain drift with temperature), small changes in the measurement geometry from one scan to the next (e.g., cylinder position on trolley, rotation);
- σ_{sys_cal} is the error in the calibration relationship between the absolute value of the measured signature and the true value of the parameter to be determined. Sources of calibration uncertainty might include an incomplete understanding of the $^{234}U/^{235}U$ ratio behavior in the facility or error in the absolute collection efficiency of the detectors.

The uncertainty budget analysis presented here includes the uncertainty components expected to be dominant in each of these categories. This analysis considers only Type 30B cylinders containing product material ranging from 2.0 percent to 5.0 percent relative enrichment, and the $HEVA_T$ and $HEVA_{NT}$ methods. The $HEVA_{hybrid}$ and the assay of M_U are not quantitatively analyzed.

Wall-thickness variations in the sidewalls of approximately 130 Type 30B cylinders have been measured by Shaw using an ultrasonic wall-thickness gauge, and a range of 12.5 mm to 13.8 mm was reported.[27] PNNL measurements on the sidewalls of 98 Type 30B cylinders showed a slightly wider range, approximately 12.7 to 14.2 mm.[10] PNNL's uncertainty budget analysis assumed this wider range. Wall-thickness variations have the greatest impact on $HEVA_T$; the effect on the neutron-based signature of $HEVA_{NT}$ is negligible compared to other uncertainty components.

The effect of UF_6 spatial distribution within a Type 30B cylinder, on the neutron emissions from that cylinder, has also been studied by Berndt.[23] This spatial distribution could depend on the temperature of the cylinder as it was filled, whether the cylinder has been homogenized in an autoclave, environmental factors (e.g., temperature cycling), and how the cylinder was handled during movement (e.g., jostled on a truck). PNNL drew on Berndt's prior work to define the range of material configurations. On one extreme, no material clings to the wall. In the other extreme, the material clings to the wall in a way that creates an annular cylinder of UF_6 sharing an axis with the steel cylinder.[23] For the HEVA instrument geometries envisioned for UCVS, the UF_6 distribution affects primarily $HEVA_{NT}$ due to perturbations in the emission, self-attenuation and collection efficiency of neutrons.

The age of the material inside a cylinder can also contribute to the variability of HEVA signatures. For example, progeny from ^{238}U grow in reaching secular equilibrium with their parent after roughly six months. This includes the grow-in of ^{234m}Pa, the main source of bremsstrahlung in UF_6, and a significant complicating factor in the accurate determination of the net 186-keV count rate in the HEVA spectra. Generally speaking, the material age affects only the gamma spectrum below ~2.0 MeV for UF_6 from natural (i.e., not recycled) uranium; the non-traditional signal is unaffected by the age unless the increase in count rate causes pileup effects. To create a distribution on cylinder age, PNNL assumed that product cylinders would leave an enrichment facility within six months of production. Note that an analysis of uncertainty budget for feed and tail cylinders would employ different age assumptions, as would the analysis of product cylinders at other fuel cycle facilities (e.g., received at a fuel fabrication facility).

As described above, uncertainty in the $^{234}U/^{235}U$ ratio behavior is a major source of systematic calibration uncertainty for any neutron-based cylinder assay method, including $HEVA_{NT}$. Variability in this isotopic ratio may take many forms, including the natural variability in ores. A survey of several open-literature studies of this variability indicate that the relative variation (mean/standard deviation) of the ratio varies from 2.4 to 5.4 percent.[22,28,29] A study by Los Alamos National Laboratory that accessed a uranium sourcing database estimated the standard deviation to be 2.8 percent.[30] Based on these findings, PNNL employed a rather broad range for natural variability in $^{234}U/^{235}U$ of ±5 percent. This broad range may partially compensate for the omission of ratio variability created by different cascades or units within the same enrichment facility, and a lack of understanding about the exact nature of the facility-specific variability. For example, PNNL has assumed a linear relationship between the $HEVA_{NT}$ signature and declared enrichment in past campaigns, but studies by Los Alamos have indicated that perhaps a quadratic relationship is more appropriate.[13]

PNNL's initial uncertainty budget analysis includes only the five components described above. Other factors that may contribute include environmental variations (e.g., temperature and humidity), ambient background variability (e.g., cylinders moving nearby), material plated on the cylinder wall or lingering in the cylinder from previous use of the cylinder (i.e., heels), and reactor-recycle feed that produces strong emissions primarily at 2.614 MeV (Figure 4).

σ_{stat} , σ_{sys_ran} and σ_{sys_cal} were calculated for $HEVA_T$ and $HEVA_{NT}$ using a Monte Carlo method. Field data recorded at the AREVA fuel fabrication plant in Richland, Washington, USA, (described later) furnished reference signal-rate calibrations for $HEVA_T$ and $HEVA_{NT}$ as observed in twelve Type 30B cylinders spanning the enrichment range from 2.0 percent to 5.0 percent. σ_{stat} was calculated by synthesizing an ensemble of quasi-random data sets from this reference calibration, with the signal rates for $HEVA_T$ and $HEVA_{NT}$ sampled in each cylinder from appropriate Poisson distributions. Computing the mean of the set of relative standard deviations of assayed versus synthetic cylinder values for E_{cyl} and M_{235} over this ensemble yielded s_{stat}. A similar procedure was applied to address systematic effects by using Monte Carlo modeling to estimate the relative impact on signal intensity of each effect of interest. Models corresponding to the expected extremes of a given parameter's range of values (e.g., wall thickness in the range 12.7 mm to 14.2 mm) established the scale for transforming parameter variations to relative signal variations. (Identical spectrum processing algorithms were applied to both data and simulation. In particular, the SWC spectrum analysis method was applied to both measured and modeled spectra in evaluating the impact of each systematic effect on $HEVA_T$.)

Notional sampling distributions for each model parameter between the extreme values were then constructed *ad hoc.* Three different distributions for each parameter were considered: uniform between the parameter extremes, and Gaussian distributions centered at the middle of the parameter interval and having standard deviation corresponding to 5 percent and 10 percent of the width of the interval. Using these parameter distributions, the Monte Carlo sampling process to generate an ensemble of quasi-random cylinder data sets from the reference calibration was repeated. The MCNP5 models were used to adjust the mean signal observed in a given cylinder based upon the sampled value of the model parameter (e.g., E_{cyl}). The analysis process is described in greater detail in Reference 26. Table 1 summarizes the results of the uncertainty budget analysis for the assay of E_{cyl} using $HEVA_T$ and the assay of M_{235} with $HEVA_{NT}$.

A comparison of the simulation-based performance estimates in Table 1 and the performance reported from multiple field campaigns with HEVA (see Table 2 below) demonstrate general consistency between PNNL's uncertainty budget analysis and field results. For E_{cyl}, field-measured total uncertainties trend well with predictions using the most pessimistic parameter distribution (uniform over the parameter range, bold values in Table 1). This finding supports PNNL's assertion that the total uncertainty for $HEVA_T$ can be largely attributed to the five uncertainty components included in Table 1. Field-measured

Table 1. Estimated uncertainty budget components and total uncertainty for HEVA assay of Type 30B product cylinders with enrichments ranging from 2.0 percent to 5.0 percent. Uncertainty budgets are given for the assay of Ecyl using $HEVA_T$ and the assay of M_{235} with $HEVA_{NT}$. All uncertainties are expressed in relative standard deviation (%) and assume a five-minute assay time. Comma-separated results for each of the relevant systematic uncertainty contributions correspond to different underlying parameter distribution models as discussed in the text, in the order (1) uniform distribution (bold highlighted values), (2) normal distribution with standard deviation corresponding to 10 percent of the parameter interval, (3) normal distribution with standard deviation corresponding to 5 percent of the parameter interval.

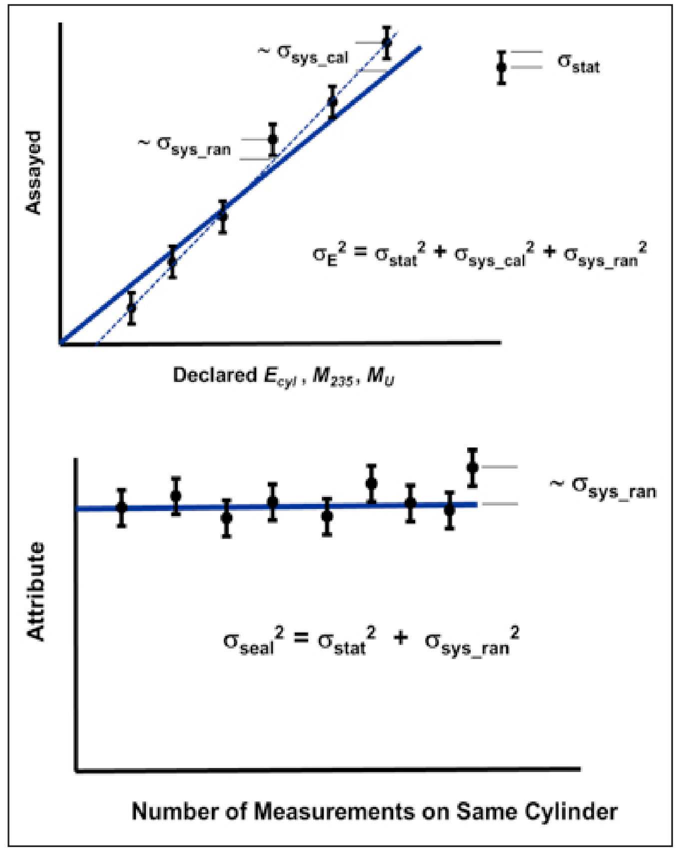
Uncertainty Component	E_{cyl}	M_{235}
Poisson statistics	0.47	0.45
Wall thickness	**3.2**, 0.18, 0.18	--
UF_6 distribution	**3.4**, 1.2, 0.58	**2.3**, 0.80, 0.40
Age	**1.9**, 0.63, 0.32	--
U^{234}/U^{235} ratio	--	**2.8**, 1.0, 0.47
Total	**5.0**, 1.4, 0.83	**3.7**, 1.3, 0.77

uncertainties for M_{235} show a relatively high degree of variability from campaign to campaign, and more investigation is needed to understand that variability and the differences between measured and predicted values. It is anticipated that variability in the $^{234}U/^{235}U$ ratio (between enrichment facilities and even enrichment units within a given facility) is the dominant factor. Larger cylinder populations, from various enrichment facilities, will be needed to support further investigation.

The uncertainty analysis presented above pertains only to the direct, absolute assay of declared cylinder parameters such as E_{cyl} , M_{235}, and M_U where the measurement scenario is a one-time assay of an unknown cylinder, followed by comparison of the measured values to the declared values. In this scenario, s_{stat}, s_{sys_ran}, and s_{sys_cal} are all important contributors to the total uncertainty, as illustrated in the left pane of Figure 5 for the assay of E_{cyl} (uncertainty analysis is analogous for M_{235} and M_U but is not shown) and in Table 1.

The uncertainty budget for the NDA Fingerprint, however, is considerably different. In that scenario, the NDA Fingerprint is collected for repeated measurements of the same filled cylinder and it is the relative *constancy and reproducibility* of the Fingerprint that is important (Figure 5, right pane), rather than an absolutely calibrated value. This means that some of the sources of uncertainty described above in s_{sys_ran} and s_{sys_cal} will be negligible or significantly less important (e.g., wall thickness variations and UF_6 distribution) while others may become relatively more important (e.g., the exact positioning of the detector field of view along the wall of the cylinder). It is expected that the total uncertainty of the NDA Fingerprint will be substantially lower than for the direct, absolute assay of E_{cyl}, M_{235} and M_U , perhaps even approaching the statistical uncertainties in Table 1. The uncertainty modeling and analysis methods developed by PNNL are unlikely to accurately capture the real-world variability of the NDA Fingerprint; such investigation is better done through future field campaigns.

Figure 5. Illustration of uncertainty components for the two primary UCVS verification roles. *Top:* the direct, absolute assay of cylinder parameters such as E_{cyl}, M_{235}, and M_U where performance is determined from the accuracy of a single measurement of that cylinder. *Bottom:* the application and verification of an NDA Fingerprint, where the performance is determined by the constancy and reproducibility of the signatures over multiple measurements on the same cylinder.



Field Measurements of E_{cyl} and M_{235}

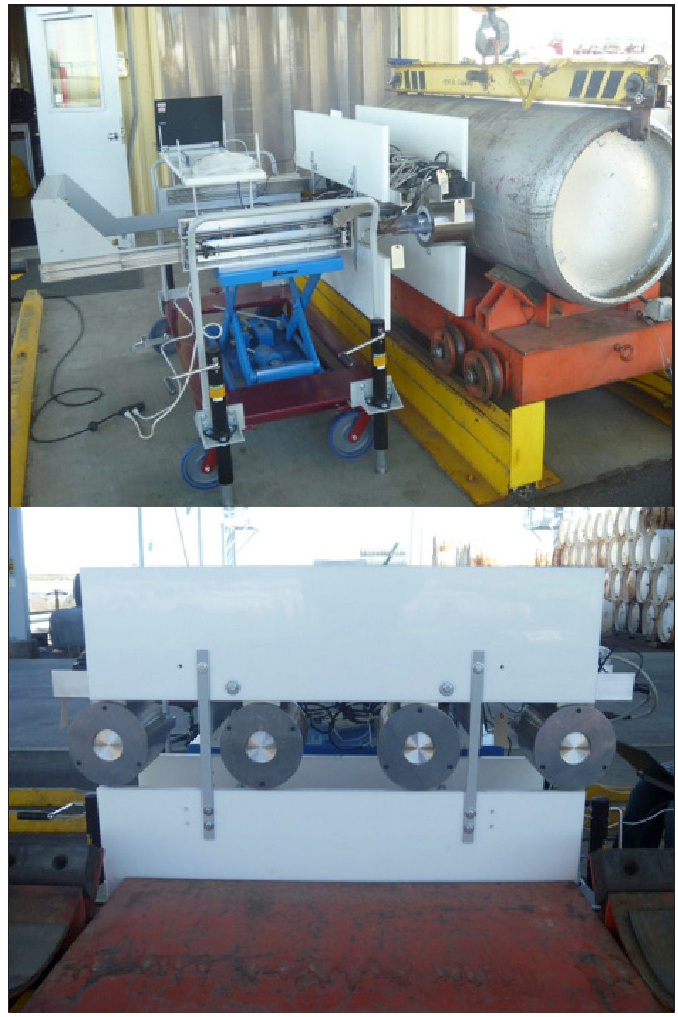
PNNL has performed several field campaigns during the development of the HEVA method, and the design of the HEVA hardware (e.g., the number and size of spectrometers, collimator design or pulse processing electronics) has evolved through those campaigns. In this section, a summary of key findings from three field trials are reported: the first two took place in 2011 and 2012 at an AREVA fuel fabrication plant in Richland, Washington, USA and the third in 2013 at an URENCO enrichment facility in Almelo, Netherlands. Photographs of the prototypes used in the most recent campaigns are shown in Figure 6.

In keeping with the IAEA's convention for reporting cylinder assay performance with handhelds, the primary performance metric here is the precision, expressed in relative standard deviation, of the measured enrichment and ^{235}U mass compared to operator-declared values. Field-measured uncertainties for HEVA can also then be compared to: a) the International Target Values (ITVs) for uncertainty in the assay of UF_6 in cylinders using handheld spectrometers [18], b) IAEA's performance targets for a UCVS,[9] and c) modeling-based uncertainty budget predictions as described in Table 1. The ITVs quoted here are based on high-resolution gamma-ray spectrometers using the traditional enrichment meter analysis technique, a five-minute count time, a well-calibrated instrument with negligible systematic bias, and the use of wall-thickness corrections using ultrasonic tools as necessary.

In addition to the three campaigns reported below, PNNL also performed an exploratory field campaign in 2010 at the AREVA facility. These measurements were focused on a side-by-side comparison of three different spectrometer/collimator designs: a 4.8x4.8 cm cylindrical $LaBr_3$ detector with a 2.5-cm lead collimator; a 7.6x7.6 cm cylindrical NaI(Tl) detector, also with a 2.5-cm lead collimator; and a 5.1x10.2x20.3 cm NaI(Tl) parallelepiped detector with alternating layers of polyethylene (two layers, each 1.25 cm thick) and steel (two layers, each 0.5 cm thick). The cylindrical $LaBr_3$ and NaI(Tl) with traditional collimator allowed concurrent comparative study of the traditional 186-keV signature for these two medium-resolution scintillators; the larger NaI(Tl) detector with specially designed collimator was used to explored the viability of the nontraditional signature. A total of twenty-three Type 30B cylinders were measured (twenty product, two natural, and one depleted). The key findings of that work were that the performance of the $LaBr_3$ spectrometer was only marginally better than NaI(Tl) for analysis of the traditional 186-keV signature, but NaI(Tl) was significantly more effective for the nontraditional signature.[5,14]

The HEVA hardware deployed in the AREVA 2011 field trial acknowledged the findings of the 2010 work, specifically the advantages of NaI(Tl), as compared to $LaBr_3$ in terms of nontraditional signature and cost. Three standard cylindrical 7.6x7.6 cm NaI(Tl) spectrometers were shielded by 2.5-cm thick annular cylinders of polyethylene (inner) steel (outer) for neutron-to-gamma conversion. A 0.65-cm lead faceplate aided collimation of the traditional 186-keV signature. A total of eighteen Type 30B cylinders were measured (twelve product, and six natural).

Figure 6. Photographs of the HEVA prototype instrument utilized in the AREVA 2012 and URENCO 2013 measurement campaigns. Four NaI(Tl) spectrometers are surrounded by specially designed shielding that collimates the traditional 186-keV signature and facilitates the neutron-to-gamma conversion process of the nontraditional signature. The polyethylene slats promote moderation of the neutron flux emitted by the UF_6 in the cylinder and enhance the nontraditional signature.



The 2012 measurements at the AREVA facility were performed using hardware very similar to that utilized in 2011, but a fourth NaI(Tl) spectrometer was added. A total of twenty-six Type 30B cylinders were measured (twenty-one product, three natural, and two depleted).

The 2013 URENCO field trial of HEVA was a part of a larger comparative study of candidate cylinder assay methods, in collaboration with Los Alamos National Laboratory, the Joint Research Center at Ispra, and Euratom.[13] The same HEVA cart used in 2012 (i.e., four spectrometers) was deployed. Over a five-day period, a total of forty-five cylinders were assayed: twenty-eight Type 30B cylinders (twenty-three product, one natural, two depleted, and two atypical), and seventeen Type 48 cylinders (nine depleted, four natural, four atypical). Atypical cylinders were those with characteristics expected to be more challenging to the NDA methods, for example reactor-recycle feed, product produced from reactor-recycle feed or tails, or very old UF_6 where daughter grow-in can complicate signatures and analyses.

A summary of HEVA field trial results for the assay of relative enrichment in Type 30B and Type 48 cylinders is given in Table 2.

Table 2. Relative standard deviation (σ_E, in percent) of measured values from the operator's declared values of cylinder enrichment for three HEVA field campaigns. The three values shown are for the 2011 AREVA, 2012 AREVA and 2013 URENCO trials (**bold**). Note that measurement times for the 2012 and 2013 trials were five minutes (ten minutes was used in 2011). No depleted cylinders were measured during the 2011 campaign (denoted as "N/A"). ITVs for handheld verification devices[18] and UCVS performance targets published by the IAEA[9] are shown for comparison.

	Product (2 percent to 5 percent)	Natural	Depleted
$HEVA_{Trad}$	4.9, 4.7, **3.4**	7.4*, 4.6*, **3.5**	N/A, 24*, **16**
$HEVA_{Hybrid}$	2.7, 3.5, **2.3**	5.6*, 2.7*, **4.9**	N/A, 19*, **7.6**
Handheld ITV	5.4	10	22
UCVS Target	3	6	9

**cylinder population of fewer than 5 cylinders*

A summary of HEVA field trial results for the assay of ^{235}U mass in Type 30B and Type 48 cylinders is given in Table 3. ITVs for M_{235} are not available because the handheld devices used today measure only a small portion (<0.1 percent) of the UF_6 volume in the cylinder and are therefore not capable of assaying the absolute mass of ^{235}U in the cylinder.

Table 3. Relative standard deviation (σ_M, in percent) of measured values from the operator's declared values of ^{235}U mass for three HEVA field campaigns: 2011 AREVA, 2012 AREVA and 2013 URENCO trials (**bold**). IAEA's performance targets for UCVS are shown for comparison.

	LEU	NU	DU
$HEVA_{NT}$	2.9, 6.9, 4.2	7.6, 1.8*, 6.3	N/A, 12*, 17
UCVS Target	3	6	9

**cylinder population of fewer than 5 cylinders*

Detection of Diversion Scenarios

Using MCNP modeling of the non-traditional neutron signature, $HEVA_{NT}$, PNNL investigated various "partial-defect" diversion scenarios in which low-enriched UF_6 was either removed from the cylinder, or substituted with depleted UF_6 (DUF_6). Presented here is a subset of those results where UF_6 was replaced with depleted UF_6 (DUF_6) such that the distance, *L*, between the exterior of the diverted volume and the extent of the original volume was equal (Figure 7).

In the analysis of detection sensitivity, a representative one-sided design (four 7.6x7.6-cm NaI(Tl) spectrometers) and a 5-minute measurement time were assumed. The $HEVA_{NT}$ net signal count rate, μ, from a full Type 30B cylinder was taken to be approximately 33 counts per second, per wt percent ^{235}U at 3 wt percent enrichment; 39 counts per second at 5 wt percent. A nominal total measurement uncertainty for $HEVA_{NT}$, σ_M = 3 percent, was assumed. These signal count rate and total uncertainty values were based on a combination of published data on $^{234}U/^{235}U$ ratios in centrifuge enrichment plants[31] and MCNP modeling of neutron emission, moderation and conversion to the high-energy nontraditional neutron signature. They are supported by field experiments, as described above.

Performance predictions for partial defect detection were calculated in terms of the probability of detection, at a given false alarm rate, for various levels of diverted material. A false alarm rate of 1 percent was enforced by defining alarm thresholds above and below the mean net counts expected for a cylinder filled with material enriched to the declared value, assuming a normal distribution: $\mu \pm 2.58\times\sigma_M$. The probability of detection for each level of missing material was determined using the probability density function (again, assuming a normal distribution) of the count rate for the corresponding count rate of the diverted cylinder. The fraction of the probability density function of the diverted cylinder that falls below the lower alarm threshold, which was set based on the distribution of the un-diverted cylinder, is the detection probability for that scenario.

Figure 7. Schematic of diversion scenario in which low-enriched UF_6 in the center of the cylinder is replaced with DUF_6. The dimension 'L' was varied to create partial defects of varying relative mass fractions.

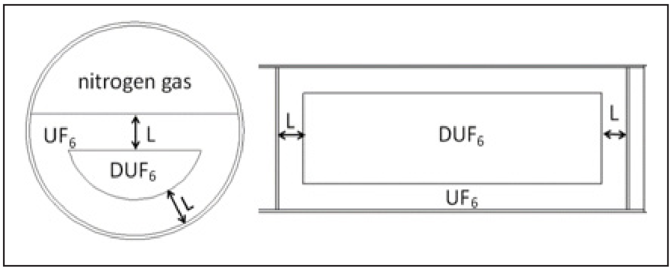
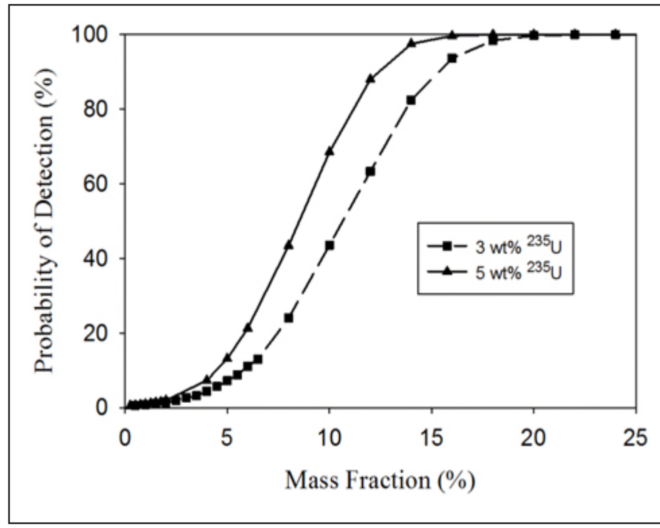


Figure 8. Probability of detection versus material substitution fraction for the $HEVA_{NT}$ assay of Type 30_B product cylinders. The detection threshold enforces a false alarm rate of 1 percent and assumes σM of 3 percent.



Results from this partial-defect detection study are shown in Figure 8. These results indicate that a representative HEVA-based cylinder assay instrument, as configured in recent field deployments described above, has the capability to detect material substitution fractions approaching 10 percent with a probability of detection greater than 90 percent and a false alarm rate less than 1 percent. Such a capability in an unattended system would be a notable improvement over the handheld assay of today, which have essentially no sensitivity to partial defects. Further improvements could be realized if the systematic components of σ_M can be reduced, for example through improved calibration approaches.

Note that the analysis above is based on the direct, absolute assay scenario where σ_M is a relatively high value of 3 percent for $HEVA_{NT}$. For the NDA Fingerprint scenario, in which the UCVS would monitor the relative constancy of the cylinder signatures on successive scans, the total uncertainty is expected to be significantly lower for $HEVA_{NT}$ because the effect of variations in the U^{234}/U^{235} ratio and UF_6 material distribution should be eliminated or significantly reduced (see Table 1). Therefore, the partial-defect sensitivity for the NDA Fingerprint, when the material diversion occurs between the time the cylinder leaves the Process MBA and the time it is shipped off-site, should be improved over the scenario of Figure 8.

Detection of Off-Normal Cylinder Characteristics

IAEA states that the UCVS NDA methods should be capable of detecting and reporting anomalies relevant to the safeguards information that must be declared by the operator, including inconsistencies between declared values of E_{cyl} and M_{235}, and the use of non-natural feed material.[9] Field campaigns have provided opportunities to evaluate HEVA's capabilities for anomaly detection.

In the 2013 URENCO field trial, nine atypical cylinders included material from non-natural origin (e.g., from reactor-recycle uranium), reprocessed tails material, partially filled containers, a cylinder with atypical wall thickness, and product cylinders that had not yet undergone homogenization. The significant variation in the $^{234}U/^{235}U$ isotopic ratio in some of these cylinders produced large variations in the nontraditional neutron signature collected by $HEVA_{NT}$ and therefore, inaccurate estimates of ^{235}U mass based on that signature alone. Using the anomaly detection logic described earlier for the hybrid analysis method, PNNL defined an internal consistency check between the direct ^{235}U signature ($HEVA_T$) signature and the ^{234}U-based signature ($HEVA_{NT}$) measured from the same cylinder. If the two independent signatures were consistent, the $HEVA_{hybrid}$ value for E_{cyl} and the $HEVA_{NT}$ value for M_{235} were reported. If an inconsistency between the signatures was detected, then a flag was issued to warn that the $^{234}U/^{235}U$ ratio in that cylinder was outside of the normal range. In that case, only the enrichment value calculated using the $HEVA_T$ signature (186-keV) was reported. For this population of atypical cylinders, HEVA demonstrated the potential to report accurate values of E_{cyl} even when the ^{234}U concentration of the cylinder was off-normal. This is a reflection of the relative independence of the traditional 186keV signature and the nontraditional neutron signature, and the verification value of a hybrid NDA method.

In all field trials to date, HEVA also demonstrated the ability to report the presence of ^{232}U via the 2614-keV gamma ray, thereby providing additional evidence to safeguards inspectorates that the cylinder contents were derived from non-natural uranium.

Summary and Next Steps

The concept of a UCVS is being explored by the IAEA as one potential technology in a new toolbox of verification measures for large-capacity enrichment plants. In recent years, PNNL has been developing and evaluating the HEVA method as a candidate technology for inclusion in the IAEA's UCVS. PNNL's novel, hybrid NDA method for cylinder verification combines a direct, familiar signature from ^{235}U with a penetrating, full-volume signature that relies on knowledge of the behavior of the $^{234}U/^{235}U$ in each enrichment facility.

An analysis of the HEVA uncertainty budget for the assay of cylinder enrichment and absolute ^{235}U mass has explored the nature and magnitude of uncertainty components that include wall-thickness variations, UF_6 distribution variation inside the cylinder, age of the UF_6 material, and potential variations in the $^{234}U/^{235}U$ ratio. Modeling-based predictions of total uncertainty for the traditional and nontraditional assay of Type 30B cylinders were found to be consistent with uncertainties measured in multiple field campaigns.

The performance results reported over a series of field campaigns indicate that an unattended HEVA method has the potential to provide assay precision for cylinder enrichment that is comparable to or perhaps better than today's high-resolution handheld devices, but without the need for tedious and laborious wall-thickness corrections. Among the reasons for this significant improvement in HEVA accuracy for cylinder enrichment, as compared to the portable methods are: a) fixed source-detector geometry that can reduce the background variability associated with portable measurements on cylinders in a storage area, b) larger detectors that cover a larger portion of the cylinder volume and therefore, reduce the impact of localized wall-thickness biases, and c) higher collection efficiency that reduces the statistical contribution to overall uncertainty.

Further, HEVA's nontraditional neutron detection method (no ^{3}He detectors required) offers the potential for full-volume cylinder assay and therefore, a new capability to safeguards inspectorates: the quantification of ^{235}U mass and improved sensitivity to material substitution or removal scenarios. A partial-defect detection study indicates that a nominal HEVA instrument is capable of detecting substituted mass fractions approaching 10 percent in Type 30B cylinders, with a probability of detection greater than 90 percent and a false alarm rate less than 1 percent. Further refinements in instrument design and calibration methods offer the potential to further improve this sensitivity.

It has also been preliminarily demonstrated that by using two different and complementary radiation signatures, the HEVA method can flag anomalies in isotopic ratios (e.g., $^{234}U/^{235}U$ or presence of ^{232}U) that might indicate the use of UF_6 material with non-natural origins, or of off-normal plant operating conditions. The HEVA method appears capable of reporting accurate enrichment assay values for such atypical cylinders, because of the independent nature of the traditional gamma and non-traditional neutron signatures.

The findings of the HEVA development efforts to date are based on relatively small cylinder populations over short operating periods, with constant supervision from trained technicians. It remains to be seen whether the potential of these methods can be realized in a cost-effective, unattended system engineered to requirements prescribed by international safeguards inspectorates and/or facility operators.

The UCVS concept is now being explored by the IAEA under the auspices of the United States and European Commission Support Programs to the IAEA. As a part of that study, PNNL will revise the HEVA mechanical and data acquisition design to reflect the requirements of IAEA's unattended monitoring systems, and further develop the HEVA analysis algorithms to support integration into acquisition and review software used by safeguards inspectorates. Long-term field trials performed with a UCVS prototype will support a definitive viability study of HEVA and the PNEM method developed by Los Alamos National Laboratory, and will include focused study on the viability of the NDA Fingerprint concept and independent verification of total uranium mass, neither of which has seen sufficient study to date. As the viability picture for a UCVS sharpens, it will be important to gain a fuller understanding of the $^{234}U/^{235}U$ ratio behavior in modern enrichment plants, and how IAEA data on destructive analysis of UF_6 samples taken from various enrichment facilities might inform the calibration of NDA methods employed in the UCVS. The ability of the HEVA methods to cope with a high degree of plating on the inside walls of product cylinders that have been filled multiple times without intervening cleaning, and empty cylinders with only heel and wall plating as source terms, also needs more investigation. A life-cycle cost estimate will be generated that is based on a HEVA hardware and software design utilizing IAEA-approved and commercially available components to the greatest extent possible. The findings of the collaborative study will inform IAEA's decision about whether to continue UCVS development and whether HEVA or PNEM, or some combination thereof, should be utilized in the next stage of testing and evaluation.

Acknowledgements

Funding for the development of the HEVA methods has been provided by the U.S. National Nuclear Security Administration's (NNSA) Office of Nonproliferation and International Security (NA-24) and the Next Generation Safeguards Initiative. The authors are appreciative to NA-24's Kevin Veal, Marc Humphrey (presently at the IAEA), Karyn Durbin, Chris Orton, and Danielle Miller for their support of this work and helpful insights, both programmatic and technical. The authors would also like to express their appreciation to AREVA NP, Inc., Richland, Washington, USA, for their support of cylinder measurement campaigns from 2009 to 2012, and to URENCO and the staff at the Almelo enrichment facility in the Netherlands for their support and coordination of the 2013 campaign as a part of a collaborative project between the NNSA and Euratom for the evaluation of candidate cylinder verification methods.

The HEVA team thanks Karen Miller of Los Alamos National Laboratory (LANL) for collegial and productive discussions about cylinder assay methods as LANL continues concurrent development of the Passive Neutron Enrichment Meter for cylinder verification applications.

References

1. Cooley, J. N. 2007. Model Safeguards Approach and Innovative Techniques Implemented by the IAEA at Gas Centrifuge Enrichment Plants. *Proceedings of the 48th INMM Annual Meeting.*
2. Lebrun, A.R., et al. 2009. Improved Verification Methods for Safeguards Verifications at Enrichment Plants. *Proceedings of the ANIMMA Conference.*
3. International Atomic Energy Agency. 2011. Research and Development Program for Nuclear Verification 2012-2013. IAEA Department of Safeguards.
4. Smith, L. E., A. R. Lebrun, and R. Labella. 2013. Potential Roles of Unattended Safeguards Instrumentation at Centrifuge Enrichment Plants. *Journal of Nuclear Materials Management,* Vol. 42, No. 1.
5. Smith, L. E. and A. R. Lebrun. 2011. Design, Modeling and Viability Analysis of an Online Uranium Enrichment Monitor. *IEEE Nuclear Science Symposium Proceedings.*
6. Smith L. E., K. A. Miller, J. Garner, R. Poland, B. McDonald, H. Nordquist, J. March-Leuba. 2014. An Unattended Verification Station for UF_6 Cylinders: Implementation Concepts and Development Status, 2014 IAEA Symposium on International Safeguards, October 2014.
7. Menlove, H. O., M. T. Swinhoe, and K. A. Miller. 2010. A More Accurate and Penetrating Method to Measure the Enrichment and Mass of UF_6 in Storage Cylinders Using Passive Neutron Self-Interrogation. *Proceedings of the 51st INMM Annual Meeting.*
8. Miller, K. A., H. O. Menlove, M. T. Swinhoe, and J. B. Marlow. 2010. A New Technique for Uranium Cylinder Assay Using Passive Neutron Self-Interrogation. *Proceedings of the IAEA Symposium on International Safeguards.*
9. International Atomic Energy Agency. 2013. User Requirements: Unattended Cylinder Verification Station. SG-UR-12186.
10. Smith, L. E., D. V. Jordan, A. C. Misner, E. Mace, and C. Orton. 2010. Hybrid Enrichment Assay Methods for a UF_6 Cylinder Verification Station. *Proceedings of the 51st INMM Annual Meeting.*
11. Mace, E. K., and L. E. Smith. 2010. Automated Nondestructive Assay of UF_6 Cylinders: Detector Characterization and Initial Measurements. *Nuclear Instruments and Methods in Physics Research Section A.*
12. Jordan, D. V., C. Orton, E. Mace, B. McDonald, J. Kulisek, and L. E. Smith. 2012. Automated UF_6 Cylinder Enrichment Assay: Status of the Hybrid Enrichment Verification Array (HEVA) Project. PNNL-21263, Pacific Northwest National Laboratory.
13. Smith, L. E., K. A. Miller, E. K. Mace, D. V. Jordan, C. R. Orton, C. D. Rael, J. Morrissey, and R. Veldhof. 2014. A Study of Candidate NDA Methods for Unattended UF_6 Cylinder Verification: Action Sheet 40 Final Report. PNNL-2294, Pacific Northwest National Laboratory.
14. Smith, L. E., E. K. Mace, and A. C. Misner. 2010. Signatures and Methods for the Automated Nondestructive Assay of UF_6 Cylinders at Uranium Enrichment Plants. *IEEE Transactions on Nuclear Science* (57).

15. McDonald, B. S., D. V. Jordan, C. T. Orton, E. K. Mace, R. S. Wittman, and L. E. Smith. 2011. Model and Algorithm Evaluation for the Hybrid UF_6 Container Inspection System. *Proceedings of the 52nd INMM Annual Meeting*.
16. Walton, R. B., T. D. Reilly, J. L. Parker, J. H. Menzel, E. D. Marshall, and L. W. Fields. 1974. Measurements of UF_6 Cylinders with Portable Instruments, *Nuclear Technology* (21).
17. Dias, F., E. A. de Luceana, B. R. McGinnis, B. Rollen, and S. E. Smith. 2008. Verification of U-235 Isotopic Abundance in Low Enriched UF_6 Cylinders by a Low Resolution Spectroscopy Technique. *Proceedings of the 49th INMM Annual Meeting.*
18. Zhao, K., et al. 2010. International Target Values 2010 for Measurement Uncertainties in Safeguarding Nuclear Materials. IAEA STR-368, IAEA Department of Safeguards.
19. Janssens, F., and J. P. Francois. 1991. Evaluation of Three Zero-Area Digital-Filters for Peak Recognition and Interference Detection in Automated Spectral Data-Analysis. *Analytical Chemistry* 63(4).
20. Op de Beeck, J. 1975 Gamma-Ray Spectrometry Data-Collection and Reduction by Simple Computing Systems. *Atomic Energy Review* 13(4):743-805.
21. Miller, K. A., et al. 2010. The Uranium Cylinder Assay System for Enrichment Plant Safeguards. *Journal of Nuclear Materials Management,* Vol. 39.
22. Richter, S, et al. 1999. Isotopic Fingerprints For Natural Uranium Ore Samples. *International Journal of Mass Spectrometry* 193(1):9-14.
23. Berndt, R., E. Franke, and P. Mortreau. 2010. ^{235}U Enrichment or UF_6 Mass Determination on UF_6 Cylinders With Nondestructive Analysis Methods. *Nuclear Instrumentation and Methods A* (612).
24. Fischer, D., et al. 2005. Environmental Sampling for Detecting Undeclared Nuclear Materials/Activities. *Proceedings of the INMM/ESARDA Workshop.*
25. Cooley, J.N., et al. 2000. Experience with Environmental Swipe Sampling in a Newly Built Gas Centrifuge Enrichment Plant. *Proceedings of the 42nd INMM Annual Meeting.*
26. Jordan, D. V., L. E. Smith, J. A. Kulisek, B. S. McDonald, and E. K. Mace. 2013. Hybrid Enrichment Assay Methods for a UF_6 Cylinder Verification Station: FY13 Final Report. PNNL-23164, Pacific Northwest National Laboratory.
27. Shaw, R. S. T. 1979. The Routine Non-Destructive Measurement of the ^{235}U Concentration of Enriched Uranium Hexafluoride in Transit Cylinders Using High Resolution Gamma Spectrometry. *Proceedings of the 1st ESARDA Symposium.*
28. Brennecka, G. A., L. E. Borg, I. D. Hutcheon, M. A. Sharp, and A. D. Anbar. 2010. Natural Variations in Uranium Isotope Ratios of Uranium Ore Concentrates: Understanding the $^{238}U/^{235}U$ Fractionation Mechanism. *Earth and Planetary Science Letters* 291(1-4):228-33.
29. Solov'ev, G. S., A. V. Saprygin, I. S. Izrailevich, and A. A. Makarov. 2002. Determination of ^{234}U Content in Uranium from Different Deposits. *Atomic Energy* 92(4):317-21.
30. Miller, K. A., H. O. Menlove, M. T. Swinhoe, and J. B. Marlow. 2013. Technical Assessment of the Passive Neutron Enrichment Meter (PNEM) for an Unattended Cylinder Verification Station (UCVS). LA UR 13-22911, Los Alamos National Laboratory.
31. Biswas, D. 1994. Potential Utilization of SRS Uranium with High U-236 Content as Commercial LWR Fuel (Study of Neutronic and Safety Characteristics). Savannah River Site, WSRC-TR-94-0370.

A Method for Assessing Safeguards Effectiveness and Its Application to State-Level Material Accountancy Verification

Jonathan B. Sanborn
JBS Consulting LLC, Arlington, Virginia USA

Abstract

A formalism for assessing international safeguards systems at declared facilities is presented and applied to safeguards for detecting diversion from a state's fuel cycle. This formalism is aimed at better understanding and documenting the logic of safeguards verification; an example is presented showing how thorny the logic of "flow verification" and "MUF = 0" can be. The proposed formalism has two steps: the first creates a "proof logic:" a set of statements that proves, at a certain level of abstraction, that the safeguards system is effective. The second step involves analyzing how any idealizations of the proof logic might be compromised in reality, for example through adversary concealment considerations. As an application of this approach, a model of state-level material accountancy verification is then presented, incorporating: locations of declared nuclear materials, nuclear material accounting declarations, physical inventory verifications, distinguishable nuclear material species and substitution possibilities, and three well-defined concepts of flow verification involving containment/surveillance and process flow measurements. It is shown that physical inventories in the state should follow certain rules regarding scope, simultaneity, and sequencing. These rules may be read off of a directed graph defined over the set of locations of nuclear material. The analysis shows that mass balance boundaries should be designed at the state level in specific ways, which in general will have to take into account containment/surveillance and process monitoring possibilities, and the nature of the species of nuclear materials, rather than facility boundaries or pre-existing accounting divisions.

Introduction

The subject of this paper is a formalism whose purpose is to structure the analysis of safeguards systems at declared locations.[1] Such a formalism aims to assess, as rigorously and systematically as possible, the robustness of a safeguards system in detecting non-compliance in the face of plausible adversary concealment strategies. This is not a new topic, and has been the subject of studies and papers dating from at least the 1980s. The author has been involved in some of these efforts, and although they have raised awareness of the need to systematically consider adversary strategies, a number of drawbacks seem to have hampered their ability to be of everyday utility to safeguards practitioners.[2]

Yet the fundamental logic of safeguards systems—why certain measures are needed to achieve the objective, and what assumptions are being made—is not always clear and is seldom documented. The approach described here attempts to provide that foundation; and the examples provided suggest that useful results may follow from such an approach. The point that care needs to be taken in thinking about the logic of verification is important enough that a detailed example is provided later in this paper.

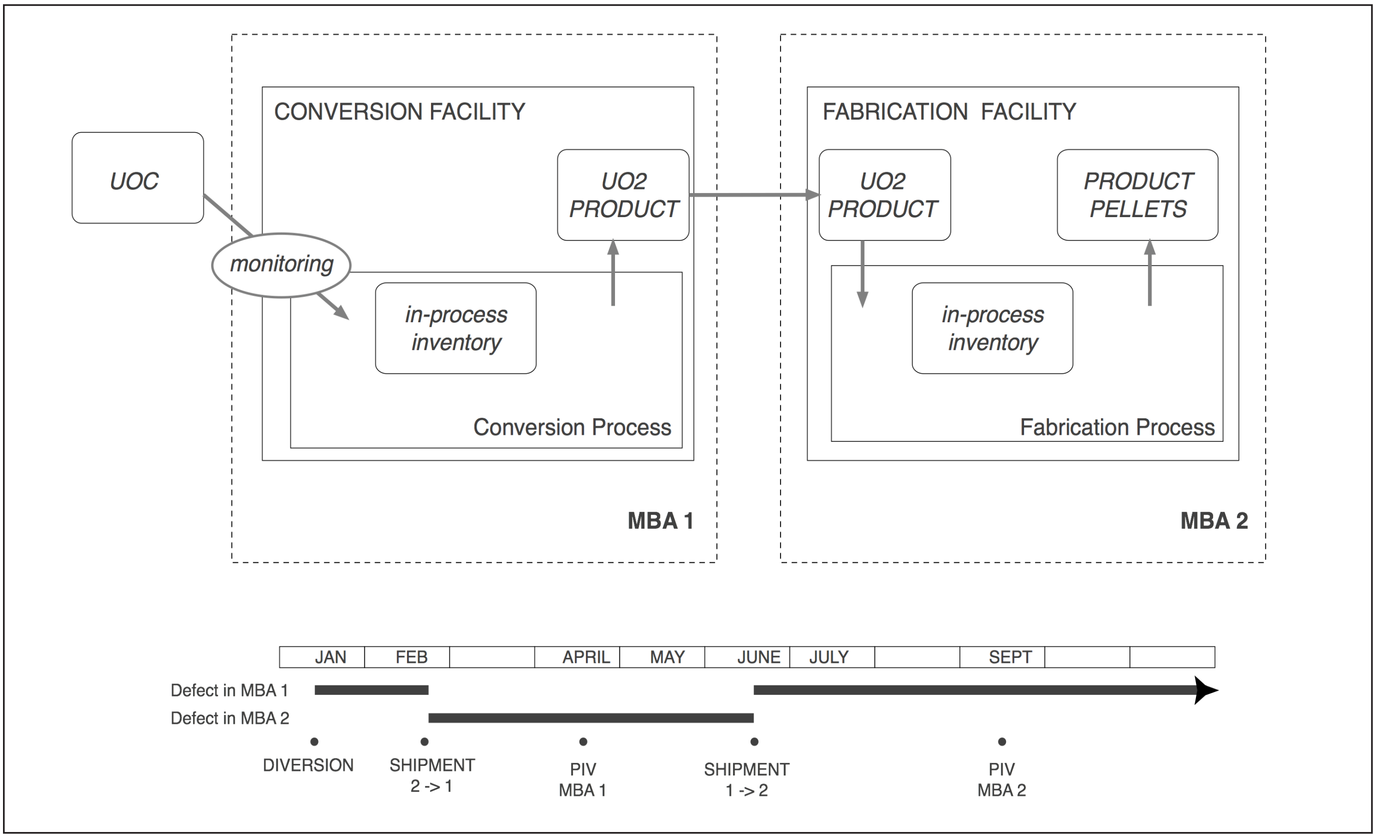
The example indicates that certain safeguards concepts need to be thought through very carefully, and that such factors as the relationship between the times of inventories, the ability to monitor the physical movements of material into and out of processes or storage areas, as well as substitution possibilities, are needed in a complete theory of material accounting verification.

The methods proposed here are intended to make the logic of a safeguards system, and the assumptions that underlie that logic as clear as possible.

An Example of the Subtleties of Safeguards Logic

We consider an example involving material accounting verification. The text of INFCIRC/153 paragraph 30 appears to suggest that in order to detect diversion, one need only verify that "Material Unaccounted For (MUF) = 0."[3] It would seem to imply that Material Balance Areas (MBAs) can be treated independently, and that the components of MUF can be confirmed by verification measurements without any fundamental require-

Figure 1.



ment for containment/surveillance (C/S) or process monitoring.[4] The following example suggests that the real situation is somewhat more complex.

The example consists of a uranium ore concentrate (UOC) conversion plant that ships purified uranium oxide to a fuel fabrication plant, as illustrated in Figure 1. We will make some unusual assumptions about these facilities in order to make certain verification issues as clear as possible. First, the input stages of the conversion plant are robustly and accurately monitored (e.g., with in-line instrumentation and C/S), so that the International Atomic Energy Agency (IAEA) can be assumed to know how much uranium has entered the purification process. The product oxide (UO_2) is held for periodic Agency inspection before being shipped; the drums of oxide are accurately measured and sealed by inspectors. At the fuel fabrication plant the seals on the oxide drums are verified at the physical inventory verification (and at other interim inspections), but we do not assume that these drums are continuously followed after that point (i.e., after they leave input storage; at some point the cans must be unsealed and fed to the fabrication process; this is not monitored), nor do we assume any in-line measurements that detect what is actually fed to the fabrication process. The fabrication process adds an isotopic spike to the uranium oxide. The fabrication process results in pellets which are measured and placed in cans (these are verified and sealed at the physical inventory verification, or PIV). We assume for simplicity these cans simply remain in storage. The conversion plant has a clean-out inventory and PIV in April, the fabrication plant has a clean-out inventory and PIV in September. These are complete inventories and there is no significant unmeasured in-process material at the PIV; but during processing operations there may be considerable unmeasured in-process inventory and hold-up.

Note that for both facilities all the components of the material balance (inventories and flows) may be said to be completely verified. Moreover, the in-process material and product at one facility cannot be substituted for that of the other.[5] We assume a verified result of MUF = 0 to a high degree of measurement accuracy, and reported (ICR and MBR) data are consistent with each other and with measurements. It would seem that all the requirements of INFCIRC/153 paragraph 30 are satisfied, and no diversion is indicated.

Yet this arrangement allows for the following diversion scenario. In January, a quantity of material is diverted from the in-process inventory of the conversion facility. At this point there is a defect[6] at the conversion MBA. In February, the fabrication plant reports that it is feeding that quantity (the quantity of material that was diverted) of oxide in the inventory in the sealed UO_2 drums to the fabrication process, but instead, it makes an undeclared shipment of that material to the conversion plant, and that material is placed in new product drums, to be presented to the inspector as new product. Because actual physical material has been added to the material at the conversion plant, the defect there goes away, and the PIV at the conversion facility in April 2000 will show MUF = 0. In June there is an undeclared shipment of oxide product from the conversion plant which is fed to the fabrication plant. Because material has now been restored to the facility it was removed from, the September fabrication facility PIV results again in MUF = 0. This cycle can repeat indefinitely.

Note the following:

- If the inventories were taken at the same time, this would prevent the movement of the defect back and forth; that would be one way to address the problem.[7]
- If there were some sort of monitoring at the input to the fabrication plant that would detect the fact that in February there was no actual feeding of material as was claimed, that would also address the problem.
- If we assume such input monitoring, but not the isotopic spike (so that the materials are now fungible[8]), that would again allow an undeclared shipment of fabrication facility material back to the conversion plant as a substitute for missing material, again creating a problem.

This example seems to indicate that at least a naïve interpretation of the concepts of verification of the components of the material balance are inadequate to rule out diversion; simply verifying "MUF = 0" does not prove compliance. The problem of course is that while the inspector seems to be verifying the flow of material between the MBAs, his measurements do not reflect what is really going on.

Defining a Safeguards System

The type of safeguards system addressed here involves planned, routine safeguards activities designed to detect diversion or facility misuse; we are not trying to model *ad hoc* investigations of allegations of illegitimate activity, or the process of looking for undeclared activities at undeclared locations. We assume that a *safeguards technical objective* can be articulated that defines what these routine safeguards are "designed to detect." This will be some statement about detection of diversion or facility misuse with perhaps timeliness and quantity parameters specified.[9] Whatever the technical objective indicates is *to be detected* we will call *technical non-compliance*,[10] and the absence of technical non-compliance is *technical compliance*.

A *safeguards system* is defined here to consist of *observations, data,* and *anomaly rules*. *Observations* are just labels for safeguards activities that produce *data* (e.g., measurements, examinations of seals, examinations of declarations, review of surveillance records, etc.). *Anomaly rules* specify when an anomaly has occurred (e.g., inconsistency in reported data, inconsistency between reported and measured values, seal tampering indication).[11] It is assumed anomalies are appropriately followed up;[12] so that for the purposes of this analysis, if non-compliance triggers an anomaly (in a timely manner if that is a consideration), the safeguards system makes a detection and therefore has satisfied the objective.

The Assessment Formalism

This formalism is aimed at determining whether a proposed safeguards system will achieve the objectives for a fuel cycle facility or a set of facilities in light of plausible adversary strategies and concealments. Given the stated objectives and description of the relevant aspects of the facilities, the formalism is a two-step process: (1) creating and assessing a *proof logic* for the safeguards system; and (2) determining whether or how that proof might be compromised by various real-world considerations. This second step examines whether certain statements are verified robustly by the observations in the safeguards system, or whether those observations and data allow for concealments which suppress the creation of anomalies.

A *proof logic* for a safeguards system is essentially a proof of the proposition: "if technical non-compliance occurs, the safeguards system will generate an anomaly (in a timely manner, if that is required)." It is a set of statements, which, if true, together logically imply an effective system. These statements might be about the consequences of non-compliance, the logical implications of earlier statements, or technical assertions assumed to be generally valid.[13] The logic model should come as close as possible to a mathematical proof. Ideally, a logic model is created as part of the process of documenting a safeguards approach.

In this first step in the process, it is acceptable to assume some statements are true, even if it is understood that this might not be the case under certain real-world conditions – those issues are dealt with in the second step. The important thing is that the logic produces a conclusion that non-compliance is detected.

Example 1. A facility storage area holds a number of containers filled with nuclear material. The inventory of containers has been previously verified, and all the containers sealed. The *technical objective* is to detect diversion (removal to a separate location) of any material. The *safeguards approach* consists of these observations and anomalies: The *observations* are an item count followed by a random checking of the seals. An *anomaly* will occur if the item count differs from the previous item count,[14] or if the seal is absent, broken, or the signature of the seal differs from that created and recorded when the seal was applied.

The safeguards logic proof might consist of a set of statements as follows.

- If material is diverted, then either (A) a container has been removed or (B) a container has not been removed, but material has been removed from a container (or possibly both A and B).
- If a container is removed, an item count anomaly would be generated.
- Material cannot be removed from a container without altering the signature of the seal. Thus if material were removed from the container but the container remained in the inventory, there would therefore be a missing seal anomaly or a seal signature anomaly.
- Thus all diversion scenarios lead to an anomaly.

The logic here is essentially that there are two ways in which non-compliance can occur, and both A and B lead to the generation of anomalies for different reasons. That logic seems fine, even if we might question the validity of some of the statements themselves.

The next step then is to look at them to see whether any statements are unjustified because they are not true, or might not be true under certain circumstances. In the above example, the first statement seems obvious, but the next few can be questioned. An item count anomaly, for example, will not occur if a dummy item replaces the diverted one. Perhaps material can be removed from the container without altering the seal if the container is penetrated in a way that does not affect the seal. Clearly if any of these possibilities are both plausible and serve to preclude any anomalies being generated, then something needs to be fixed. On the other hand, if no such possibilities exist, we have convincing evidence (in fact, an acceptable proof) that our safeguards system is sound.

Within this formalism, the search for adversary concealment possibilities that might prevent an anomaly is highly structured; we can write down a very specific formula for them, based on the conditions of the statement, and the conditions for the anomaly, which can be clearly stated. For example,

(Container removed) AND NOT (item count anomaly).

Because we define anomalies quite explicitly in the safeguards approach, we know that an item count anomaly occurs when the observed number of items on inventory does not match a number in an inspector's files. Given that a container has been removed, the anomaly could be suppressed by changing the number of items on inventory again (dummy item), or by changing the number in the files (which might be ruled out as implausible).

Example 2. The example involves a centrifuge facility declared for low-enriched uranium (LEU) production. The *safeguards technical objective* is to be the detection of the production of a specified quantity X of highly enriched uranium (HEU), with an enrichment exceeding Y% within a specified time period T.[15] During initial DIV a set of baseline environmental samples are taken from a defined set of surfaces. The safeguards approach involves short-notice random inspections in which environmental samples are taken from some of those locations. An anomaly occurs if the samples show significant enrichments that are above Y% and inconsistent with the baseline data.

The proposed proof logic is:

- There are four ways that the cascade might be configured, and feed introduced, and product withdrawn, to produce the X quantity of Y% HEU.
- All of the four methods will result in the migration and

airborne deposit of at least a certain specified density of HEU-bearing particles from the process on the identified set of surfaces within or around the facility.

- Swipe sampling of the designated areas will pick up the particulates and subsequent analysis will result in an anomaly.

The first two statements are technical assertions whose validity can presumably be evaluated technically for a particular cascade technology and design. If there is a plausible way to operate the cascade and feed and withdrawal operations to make HEU for which the second statement is not true, it represents a problematic adversary strategy. In any case, the dependence of the effectiveness of the safeguards approach on certain technical assumptions that may make it appropriate in some circumstances, but not in others, is made explicit. Since things like cascade technology may change with time and location, it is important to have such dependencies documented.

For the last statement, the question to be analyzed is whether there are any adversary strategies that can avoid detection of an anomaly if the HEU particulates were in fact present on the relevant surfaces. This step then requires consideration of a situation where HEU particles are dispersed, but the anomaly does not occur. The anomaly is very well-defined, and involves a comparison between baseline and inspection-generated swipe data. To suppress the anomaly, the observed measurement data have to become consistent with the baseline data. This condition can again be expanded as a set of logical possibilities: it might happen if there are no HEU particles in the swipe sample analyzed, or if there are such particles, but the baseline data also show a similar signature. The first possibility might point to some sort of cleanup scenarios;[16] the second may not be plausible if it is already known to be false, but it does point to a situation (a past history of HEU production) in which this safeguards approach may not be viable.

To summarize the formalism: one writes down the proof logic, makes sure the logic itself is sound (assuming that the statements are true) and then one looks at ways that the validity of the statements could be called into question. If they are faulty, or there are adversary concealments which are plausible and suffice to suppress the anomalies, one needs to go back and find fixes; otherwise one has a solid logical foundation for a safeguards system.

A Model of Diversion Detection at the Level of the State

One way to think about the formalism just described is that the proof logic represents an abstract model of the safeguards system, containing idealized characterizations of the safeguards measures[17] that are sufficient to provide the necessary proof of effectiveness. These documented characterizations or assumptions can then be analyzed.

Using this approach, we now consider a more complicated safeguards problem, having to do with detection of diversion. The example in the second section of this paper suggests that it would be naïve to assume that verifying that "MUF = 0" suffices to show the absence of diversion; so we cannot base a proof logic *only* on this idea. We describe here an idealized model composed of a number of idealized safeguards elements, and show how that model behaves, and necessary conditions for safeguards effectiveness. Later we provide the proof logic for a particular case of such a model.

This model is intended to address the "classical" problem of material accounting verification, in which PIVs are done on a defined schedule, and where between these PIVs there may be un-measurable in-process inventory. It assumes highly accurate material verification measurements.[18]

Model Concepts

The model is based on a set of assumptions according to the following definitions.

Nuclear material, inventory locations, and diversion

- *Material Inventory Locations (MILs).* These are locations where nuclear material is declared to reside for verification purposes. It is a generalized "MBA" concept that could encompass a single can of material, or a whole process area that might be inventoried at one time. Flows into and out of an MIL are assumed to be known to the operator and thus can be declared.
- *Diversion.* Permanent removal of material from an MIL to an undeclared location.

Substitutable. Material in MIL A is substitutable for material in MIL B, if it is plausible that a PIV at MIL B would *not* detect the material from A (or material that could plausibly be generated from material from A[19]), if it were placed in MBA B, and so the amount of this substituted material would be credited to MIL B at the PIV. If two batches of material are mutually substitutable they are *fungible.*

Material species are a class of nuclear material that is to be considered uniform for the purposes of safeguards. This is a term of convenience; the analyst decides what he wants to call different species, but all material within a species should be fungible. Uranium and plutonium are certainly different species as they are reported separately and an inspector will always be able to distinguish them.[20] Two different types of material that we assume cannot be transformed into one another, and which safeguards observations can distinguish, should be designated as different species.

Declarations of material movements:

- *Normal material flows and inventory species*. The process flows of material between MILs and the types of materials that are normally processed are assumed to be indicated on DIQs.
- *Declared flows* are the amounts of material the operator declares move from one MIL to another (shipments and receipts from one MIL to another).[21]
- *(MIL) Book Inventory Value*: The last PIV inventory value for this MIL[22] plus declared receipts minus declared shipments from the last PIV to the present time.
- *Defect*. A positive value of: (book inventory value minus the actual amount of material) in an MIL.

Safeguards elements:

- *Physical Inventory Verification (PIV)*. A verification measurement of the amount and species of material in an MIL at specific (inventory-taking) time.
- *Review of the consistency of declarations.*
- *Monitored Material Inventory Location (MMIL)*. An MIL where the initial inventory is known, and all flows into and out of a closed surface surrounding the MIL are observed by the inspector and accurately and continuously[23] verified. This is an abstract concept of an inventory location monitored by C/S, with flow monitoring if there are flows. A can of powder with a verified content and a seal might be an MMIL because the flows can be verified to be zero. A centrifuge cascade where the feeds and withdrawals are monitored, and steps are taken to assure there are no undeclared additions or removals, would also be an MMIL.
- *Monitored Flow Point (MFP)*. A point at a declared process location in a facility where the inspector is able to verify or monitor the creation of a material species from another,[24] and the amounts of material created. (In a reprocessing plant, one monitors the shearing cell, dissolver, and input accountability tank to determine the amount of dissolved plutonium produced. Another example is mass and enrichment monitoring at the product withdrawal point of an enrichment cascade.)

Note that this model contains a concept of inventory verification, and concepts of flow verification: flow as movement into a physical volume of space monitored by C/S, and flow as transformation from one (distinguishable) species of material to another.[25]

The safeguards problem in this instance is the detection of a diversion within some defined timeliness criterion. The safeguards system associated with this model involves the following set of observations and anomalies:[26]

a) A PIV will detect as anomalous any difference between the book inventory and the actual inventory.
b) A PIV will detect as anomalous a material species—not substitutable for the one declared to be on inventory—that is present, but not declared to be present, at the PIV.
c) The consistency review will detect as anomalous any declared flow that is not consistent with normal (DIQ-declared) flows.
d) The safeguards measures associated with an MFP will detect as anomalous any difference between the actual and declared amounts of material processed (at the declared process point)[27] into a different material species.
e) The safeguards measures associated with an MMIL will detect as anomalous any difference between the actual and declared values of flows of material across the physical boundary of the MMIL (including any undeclared movement of material).

A complete description of a safeguards system for a specific set of facilities would require a prescription for the scheduling of the PIVs. That is derived from analysis below.

Diversion-Detection Analysis

Game Configuration

In what follows, we assume a set of MILs, for which normal material flows are defined (see the example in the Appendix). At some initial point in time, there are declared book values for all the MILs that correspond to the actual inventories (no defects). Based on this set of data, we consider a game played between the state and the inspector, where the state diverts and tries to avoid detection, while the inspector tries to detect the diversion, based on the anomalies listed above. There is a timeliness goal for detection (we will not pre-judge what value can be achieved, but initially assume one year). PIVs are scheduled in advance and the state knows the timing.[28] Obviously if the inspector could schedule inspections all the time everywhere, he would do so and potentially detect any diversion instantly. But in practice the IAEA has to minimize the number of inspections,[29] and we assume PIVs in process areas cannot be required more frequently than yearly. Clearly the inspector must inevitably fail a yearly detection requirement unless he makes at least one inspection per year for each MIL, so we assume initially he makes one inspection per year per MIL.

The state chooses when and where to divert material, when and where to move material, and what to declare in terms of flows between MILs. There are a number of things that will result in immediate anomalies: declaring a non-normal flow, declarations of false flows or inventories in an MMIL or false flows through an MFP.

As will be seen, the game that results from this model might be called "chase the defect," as the adversary will move the defect to avoid having a defect in any MIL which is having a PIV.[30]

Adversary Defect Propagation Options

If a diversion occurs at a particular MIL, the absence of material immediately creates a defect; eventually that MIL will be scheduled for a PIV, and the state must consider how to avoid the defect in that MIL being detected by the PIV. Since a defect is a difference between the observed PIV and book inventory, the defect can be made to disappear by (1) increasing the actual amount of material at PIV (without increasing book value), or (2) decreasing the book value (without decreasing the actual amount of material); this decrease can be achieved by overstating outflows or understating inflows.

Under the safeguards measures described, we then have the following possibilities for undetected movement of a defect (where neither MIL A or B below can be MMILs, as this would result in immediate detection):

- If MIL B has material that is substitutable for that in MIL A, a defect can be moved from A to B by making an undeclared movement of material from B to A.
- If there is a normal flow of material from MIL B to MIL A, and if that flow is not monitored by a (strong) MFP, a defect can be moved from A to B by understating the amount of material flowing from B into A.[31]
- If there is a normal flow of material from MIL A to MIL B, and if that flow is not monitored by a (strong or weak) MFP, a defect can be moved from A to B by overstating the amount of material flowing from A into B.

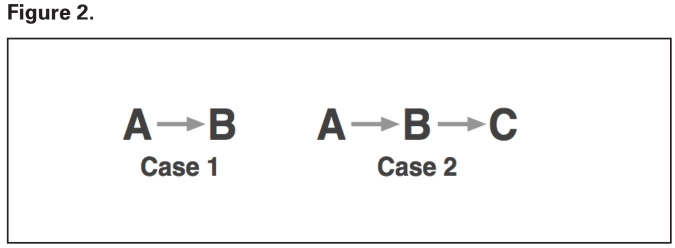
We will also assume that if a defect can be moved from MIL A to MIL B, and if a defect can be moved from B to C, it is possible to move from A to C;[32] so combinations of these paths are valid moves. Given assumptions about what materials are substitutable, this logic leads to a set of possible paths a defect can take that may be represented by a directed graph over the set of MILs, as shown in figure A2. We can call this the "defect path graph" of the MILs.

PIV Scope, Simultaneity, and Sequencing

If in this graph, there is a loop (such as B to C to B in figure A2), the set of MILs on that loop must have inventories taken simultaneously, otherwise the anomaly can be passed back and forth between the MILs on the loop indefinitely, exactly as was illustrated in the example in Section 2. Since these combined MILs are inventoried at the same time, each set can now be thought of as an "effective MBA."

We then consider a reduced defect graph, where all the MILs in loops have been combined into single inventories (see Figure A3). There are no longer any loops in this diagram, so that if one proceeds from any given point along a path in the direction of the arrows, one is forced to come to a halt at some point. Consider a structure like Case 1 below within such a diagram:

Figure 2.



First assume that the PIV at A takes place January 1, and the PIV at B takes place February 1, 2000. Suppose, immediately after a PIV at A, there is a diversion from A. A year later, there will be another PIV at A, so that the state has to move the defect away from A, to B. By February of 2001 there will be a detection at B, because the defect cannot be moved out of that location.

Now assume (same Case 1) that the PIV at B is in January, and the PIV at A is in February. A diversion takes place from A after the February PIV in 2000; and the state moves the defect from A to B at the end of January 2001. Now the detection does not take place until January 2002 – almost a year later than before.

Thus one can see that there is right and a wrong sequence for the PIVs. One can see that if the time sequence is correct, the defect is "chased into a dead end" in the fastest time – that time being one year plus the time interval between the beginning and end of a path. In Case 2 above, using the same logic and tactics, one can readily see that if the timing of the PIVs is wrong – in this case C then B then A – it will take almost three years for a defect to be forced to C from A and be detected; whereas if the sequence of PIVs follows the sequence of arrows on the diagram, the detection will take place again in one year plus the time between the A and C inventories.

Implications for Diversion Detection in the Model

We can draw some conclusions from the foregoing analysis about timely detection of diversion, when substitution and undeclared shipment scenarios are assumed to be possible, and when flows can be physically monitored as described in MMILs and MFPs.

1. There must be a PIV at every MIL with some periodicity, otherwise the state could simply divert from that MIL without a PIV. It makes sense that this period should be uniform, otherwise the state could just pick the longest interval and divert at the start of that time period. We will assume that there are PIVs at every MIL yearly.
2. Clearly, the inspector cannot expect to do any better than detection in this one-year period.
3. Unless inventories are undertaken simultaneously at MILs on loops in the defect diagram, the state can rotate defects through these MILs indefinitely without detection. These sets of MILs that are inventoried together are effectively MBAs.
4. Two MILs that follow one another along a declared flow path which is not monitored (no MFP, no MMIL) will have to be in the same effective MBA. This is because a defect will be able to propagate both ways: there can be a declared flow without a real flow, or a real flow without a declared flow. Thus MBAs should have some sort of effective flow monitoring[33] at their boundaries.
5. Inventories should be taken close together in time and in the order of the arrows on the defect diagram.
6. Given that inventories are taken simultaneously in effective MBAs, and inventories in the order described in (5), then *one should be able to show*[34] that the worst-case detection time is one year plus the longest-time path on the diagram; this path time can be arbitrarily small but will not be greater than a year.

It is not difficult to see the sorts of safeguards structures that will be produced from this model: basically, PIVs will be simultaneous over sets of MILs with similar materials in them, and these sets will be bounded by some sort of physical flow monitoring. Certainly, material balance structures should be designed at the level of the whole state to accomplish this.

Assessment of Safeguards on a Fuel Cycle

In the Appendix there is a description of a state's fuel cycle, MILs, and monitoring points. We assume a safeguards system as described by anomalies identified in points a) - e) in Section 5.1, where the PIVs are done yearly on the following schedule:

- MIL A: January 1
- MILs G and H: February 1
- MILs B, C, F: March 1
- MIL K: April 1

The non-PIV anomalies c) – e) of 5.1 can be thought of as being monitored on a frequent periodic basis.[35] We also take as assumptions the policy decisions about substitution possibilities identified as f) - l) in the Appendix.

Step 1 – Proof Logic

A proof logic for this safeguards system would consist of those statements a) - l) along with the following:

- Diversion, by definition, must occur as a permanent removal from at least one of the MILs A – L (by assumption enrichment plant tails would not be diverted)

- If the removal occurs in MILs D, E, J, or L, since these are MMILs, according to e) there will be an immediate anomaly and therefore immediate detection.
- If the removal occurs from MIL K, detection will occur by the subsequent April 1, because:
    - The removal creates a defect at MIL K. If the defect remains at the next April 1, there will be a detection according to a).
    - According to the definition of defect, one can only erase it by increasing the actual inventory or the decreasing the book inventory.
    - One can increase the actual inventory by an undeclared movement of material (substitution), or a declared movement of material to MIL K. This material has to come from another MIL.
    - According to a) and g) if actual inventory is changed by substitution, there will be a detection at the PIV in April, because no other material in the state is substitutable.
    - A declared movement of material that does not produce an anomaly of type c) must be a flow of material from MIL L; moreover, one must overstate the flow to increase the book inventory. But since L is a MMIL, if the declared flow out of L is not equal to the actual flow, there will be an anomaly. But if the two are equal, both the book and actual inventory in K will be increased equally, and the anomaly will persist and be detected in April.
- If the removal occurs from B, C, or F, *or if a defect otherwise occurs in these MILs*, detection will occur by the following March 1. This is due to the same type of reasoning as in the above tic: to use shorthand, the defect is stuck in BCF. There are no materials in the fuel cycle that can be substituted for the BCF material—see g), h), i), and k)—and one cannot (with one exception) overstate or understate flows into or out of the BCF inventories, because they are all monitored as either MFPs or MMILs. Because of the assumption that the fabrication plant MFP could be bypassed, it is possible to *understate* that flow, but one cannot *overstate* it without detection, which is what is needed to move the defect from F to G.
- If the removal occurs from A, detection must occur either at the following January 1, or if not, two months later on March 1. This is because, if nothing is done, the defect will cause an anomaly on January 1 via the PIV. The defect cannot be removed by understating imports or overstating feed to the enrichment cascade, because both would be detected (MFPs). According to f), material from B, C, or F could be used as a substitute, and might be borrowed before January 1 erasing the defect in A, but this would cause a defect in BCF, and, according to the previous tic, this defect must be detected by the following March 1.
- If the removal occurs from G or H, detection must occur either at the following February 1, or if not, one month later on March 1. If nothing is done, the defect will cause an anomaly on February 1 via the PIV. The defect cannot be removed by overstating product shipments to J as this is an MMIL. According to l), material from B, C, or F could be used as a substitute, and might be borrowed before January 1 erasing the defect in GH, but this would cause a defect in BCF, and according to the previous tic, this defect must be detected by March 1.

The logic shows that all possibilities lead to an anomaly, and detection will occur within fourteen months of diversion, if all of the assumptions are true. Although the logic here is non-trivial, it does not take up more than two or three pages, and it would not be a great burden to reanalyze it if some of the assumptions were to change.

Step 2 – Review of the Elements of the Proof Logic

The next step as described above is to look at the individual statements in the proof logic and see if one has confidence in them (because this is the step that compares these statements with "real" circumstances—a real state and real instruments—we will do a cursory job of this). This would start with the statements a) to e) that describe the generation of anomalies (we regard the statements f) to l) as policy choices). Under "a)" one might question whether a PIV based only on ICVD of a separate storage spent fuel pool is vulnerable to certain types of adversary strategies. This is also the place to note that if the PIV involves random strategies, they may fail simply by chance.

In practice, the safeguards system that constitutes the MMIL at the enrichment cascade would consist of a whole set of C/S and process monitoring methods, which would be described as a more detailed and complex set of anomalies, and require a separate sub-analysis to see whether the simple statement "e)" is justified. But this could be done by the same methods described here. The same holds true of the C/S systems at the power reactors.

Most of the statements in the main body of the proof above are logical consequences of the definitions and the assumption of diversion. However, the sentence

"This material has to come from another MIL."

in the third bullet of the third tic above is taken as valid because we are assuming that under full scope safeguards there is no other material available, and that the material already diverted is being used in a weapons program and unavailable. This might have to be reconsidered under 66-type safeguards.

Concluding Remarks

Many attempts to assess the effectiveness of safeguards have relied on the idea of listing *diversion paths*.[36] A diversion path is a scenario identifying the way in which material might be diverted and the diversion concealed. In theory, if one can show that the safeguards system will detect all plausible paths, one demonstrates the effectiveness of the system. In the experience of the author, such schemes generally run up against a number of problems. Since these paths are basically fictitious, and potentially infinite in number, they have to be constructed and chosen largely out of thin air, and thus tend to be analyst-dependent. These methodologies tend to identify such paths by the hundreds or thousands, and the results are unwieldy and hard to grasp or modify. There is always the problem of showing that all plausible paths have been identified.

The approach taken here turns diversion path analysis inside-out. Instead of trying to identify all the ways a system can fail, one comes up with a direct proof that it must succeed. Because the real world is too messy to capture in a rigorous proof, the trick is to make a number of assumptions or idealizations that allow for a proof to be constructed; one then looks at possible flaws in these assumptions as they apply to the real world. This approach makes clear the logic upon which the safeguards system is constructed, and the assumptions that it entails. The search for flaws can proceed in a very circumscribed and systematic manner. The results should be easier to grasp, modify, and document.

The examples presented show that this safeguards logic can be complex, even when we are dealing with "simple, classical" material accounting verification. The complexities with respect to verifying material accounting stem from the following considerations:

- In general, during bulk processing operations at nuclear facilities, there may be inventories of nuclear material that cannot be verified by the Agency; only at the PIV is all nuclear material required to be in verifiable form.
- In general, PIVs cannot be done simultaneously across all MBAs in a state.
- In general, an international inspector does not always directly observe the flow terms (additions and removals) of a material balance; he may be able to measure items which are presented to him as additions or removals, but without additional C/S measures he does not know where that item goes after he measures it. Nor, in general, does he know if other (undeclared) items enter or leave the MBA.
- In some cases nuclear material must be considered fungible, so that material from one location might be substituted for material in another location without being detected.

Taken together, these conditions may allow diversion and concealment possibilities whose safeguards solutions may not be obvious. The concept of "flow verification" must be defined very carefully. The possibility that defects may be able to move from one MBA to another means that each MBA cannot be considered independently; therefore a state-level analysis of diversion detection is needed. PIV measurements, flow monitoring possibilities, and containment/surveillance must all be considered in this analysis. Such a state-level analysis results in constraints on the boundaries of MBAs, and a surprising set of requirements on the scope, simultaneity, and sequencing of PIVs.

Jonathan B. Sanborn received a PhD in applied mathematics in 1975. After a post-doc position at the State University of New York at Stony Brook, he joined Brookhaven National Laboratory, where he worked on arms control and safeguards studies. He worked briefly for the IAEA as a cost-free expert, and was a part of the U.S. delegation to the Conference on Disarmament as technical advisor to the ambassador during the Chemical Weapons Convention negotiations. In 2000, he joined the U.S. Department of State, where he worked on IAEA safeguards issues as well as the Fissile Material Cutoff Treaty. He retired from the State Department in 2011. He now works as a consultant.

Appendix: Fuel Cycle Example

Figure A1 shows a state's fuel cycle, including imports, exports, enrichment, fabrication, reactors, and separate storage. The inventories within rounded rectangles are considered bulk material MILs; although the material may be in containers, they are not sealed and one must verify their contents by measurement (the spent fuel is verified by ICVD). The inventories within double lines are MMILs and considered under C/S; the assumption is that the inspectorate monitors and knows the material flows into or out of these locations and thus always knows what is in these inventories.[37] There is monitoring at the declared flow point (MFP) into the fabrication process; this monitoring measures the amount of UF_6 being processed, and assures that it is processed into a non-UF_6 form. The fabrication plant as a whole is not, however, monitored for undeclared flows as is the enrichment plant; so we assume it is plausible someone could introduce UF_6 into the process away from the MFP.

We will make the following assumptions:

f) It is plausible that LEU might be down-blended to substitute for natural uranium.

g) It is implausible that the spent fuel be substituted for anything else, or that anything else is can be substituted for the spent fuel.

h) It is implausible to divert natural uranium, enrich it in a clandestine facility, and substitute it for an LEU inventory.

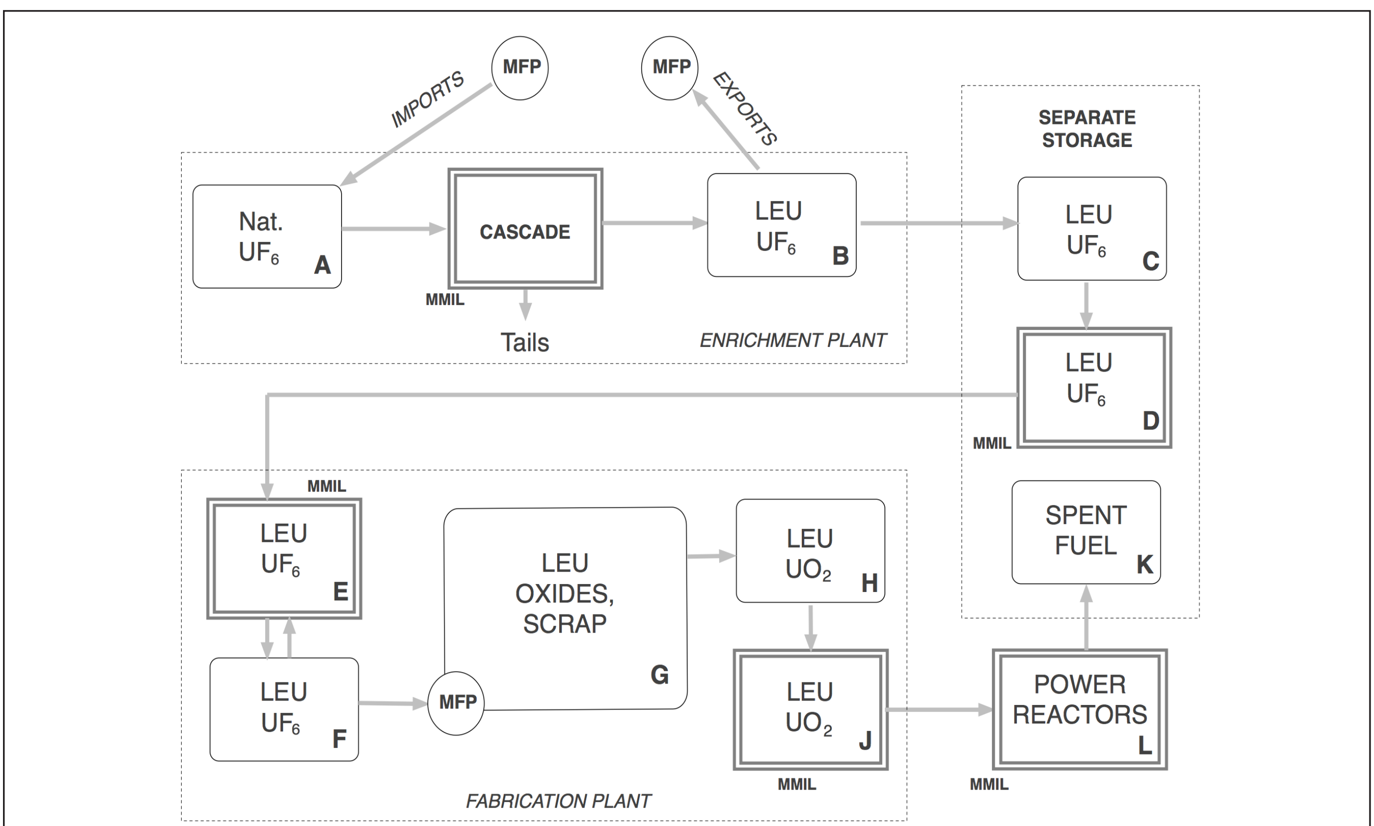
i) It is implausible to divert LEU UO_2 (from the process stream after the monitoring point, in G and H), process it back to UF_6 in a clandestine facility, and substitute it for LEU UF_6.

j) The Inventories in G and H are very similar and thus fungible.

k) It is implausible to divert tails, nor are tails substitutable for any other inventory.[38]

l) It is plausible that LEU UF_6 could be substituted for GH materials, or that such material could be introduced into the start of fabrication process in a way that bypasses the MFP at the input (this is a "weak MFP" as defined above).

Figure A1.

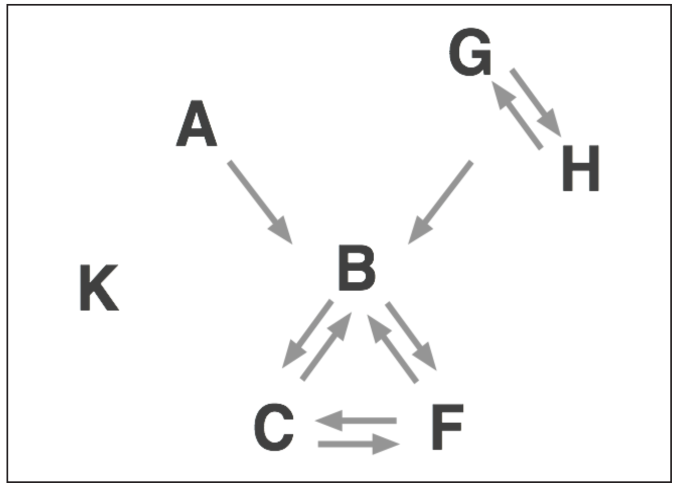


One might choose other assumptions; these have been chosen for purposes of illustration. Let us consider how a diversion from one of these inventories might be masked by somehow moving the defect to another location.

- By assumption, inventories D, E, J, and L are under C/S and thus any diversion would be detected. These inventories cannot serve as a source of material for substitution. Nor can the adversary use a strategy in which he claims to ship material to these locations but does not in fact do that. We assume that the nature of the C/S around these locations would cause these strategies to be detected immediately.
- The "imports" and "exports" are material and declarations supplied by another state or cross-checked; assuming no collusion reported data will be correct, so that if one tries to incorrectly declare the value of an import or export, it will be detected.
- Diversion from inventory A might be covered up by substitution from B, C, or F according to assumption (f). Thus a defect can be moved from A to B, C, or F.
- Inventories B, C, and F are all fungible. But by assumptions (h) and (i), we cannot substitute inventories A or H for these materials. If the cascade input and output were not monitored, one could in effect substitute A for C by undeclared extra processing of natural material into LEU; but this would detectable in our case. Similarly, we cannot move a defect from F into G by overstating an outflow from F into G because of the (weak MDP) monitoring. Thus we conclude that a defect may be moved freely between B, C, and F, but not elsewhere.
- If we divert material from G or H, it could be concealed by using material drawn from B, C, or F and inserting into the G process (the MFP monitoring does not preclude undeclared additions). Thus a defect can be moved from G or H to B, C, F.

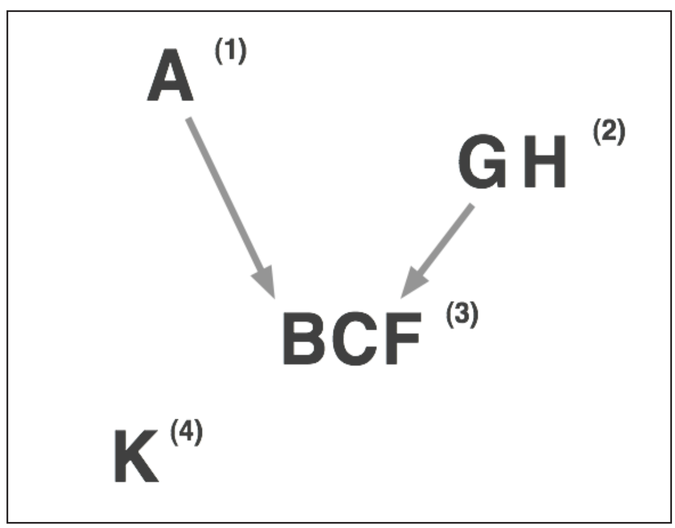
These conclusions lead to a diagram indicating how a defect can move. This is shown below (we do not include the MMIL inventories because their monitoring renders them irrelevant).

Figure A2. Defect graph



B, C, and F must be verified at the same time,[39] otherwise one can pass the defect around indefinitely as in the first example. The same logic applies to G and H. This leads to a reduced diagram that has no loops:

Figure A3. Reduced defect graph and inventory sequence



In this diagram a proposed numbering for the sequence of the PIVs in the state is indicated. Of course any numbering where A and GH precede BCF would be acceptable. If this ordering is used, then it appears that the worst-case diversion scenario occurs when a diversion occurs at A just after it has a PIV; if the defect is moved from A to BCF before A's next PIV, detection will occur at the following BCF PIV. Thus the worst-case detection time is one year plus the time interval between the A PIV and the BCF PIV.

End Notes

1. In the language of the "state level approach" this involves what the IAEA identifies as objectives relating to detection of diversion and facility misuse. See Reference 6, for example.
2. We return briefly to the subject of the history of diversion path analysis approaches to safeguards evaluation in the final section of this paper; but the approach taken here differs considerably.
3. This is not to suggest that sophisticated practitioners of safeguards don't understand that other considerations are involved.
4. This paper unavoidably contains much IAEA jargon (MUF, C/S, MBA, PIV, etc.,) whose definitions can be found in the IAEA's Safeguards Glossary.
5. We assume that inspectors are able to detect the presence or absence of the isotopic spike.
6. In this paper we will define a "defect" as the difference between the book inventory (what is declared or supposed to be in a location) and what is actually there. If one were able to take a verified inventory where there is a defect, MUF would not be zero (neglecting measurement uncertainty and holdup), indicating a diversion.
7. State-wide simultaneous inventories would solve many of the problems posed by these material accounting examples, but that is usually impractical from both the point of view of the inspector and operator. One could also consider advanced systems with real-time mailbox declarations and random inspections and so on; but here we consider the basic "classical" case where in-process inventories may only be accurately measured at PIV.
8. We will use the word fungible to indicate when materials are not distinguishable, so that one might be substituted for the other.
9. This technical objective may well be narrower than "detection of any activity which is non-compliant with a state's legal obligations." This does not mean that in practice these other situations are ignored, but routine inspection planning must focus on a practical objective that is achievable with the resources and technology at hand.
10. The idea of technical non-compliance is that it may be narrower than legal non-compliance. Thus, the diversion of one gram of material from a bulk handling facility for making a weapon is illegitimate, but we do not design *routine safeguards activities* to detect this.
11. Formally, an anomaly rule is a two-valued (yes/no) function of some set of safeguards data.
12. The follow-up actions are assumed to be perfect in that they discriminate between real problems and false alarms; this second level of safeguards activities is of course important, but beyond the scope of the paper. The IAEA, in reality, cannot afford to make a false accusation, and therefore when confronted with an anomaly must take a series of steps to "resolve" it. These non-routine investigations are generally *ad hoc* in nature and can be extremely simple (finding a typo) or long and complex (Iran investigations); but they do not seem to be amenable to advance planning or modeling.
13. These might be purely technical assumptions, like "there are four specific ways of producing HEU in an LEU-designed centrifuge," or technical assumptions one is willing to make in order to get to a provably effective system, such as "any movement of spent fuel out of a spent fuel pool must be made using a cask." The second step of the methodology may turn up ways for these assumptions to be compromised, so that these assumptions are not merely taken for granted.
14. In practice the item count might be compared to an inventory listing, which might be compared to a declaration, which is also compared to a previous item count, and all these comparisons might generate anomalies; we seek to simplify this for the present purpose.
15. It may not be obvious what the technical objective should be in some situations. If the facility is legitimately producing 19% material, it is not going to be easy to detect production at 20.1%, so some higher value could be appropriate. But one cannot rationally design a safeguards approach without knowing what it needs to be able to detect, so some parameters need to be chosen.
16. This point in the analysis is also where issues of random selection are raised. Sometimes an anomaly will not occur just because of random selection.
17. E.g., a seal will always detect removal of material from a container, a camera will always detect the movement of a cask.

18. In other words, there is an assumption that any discrepancy between a declared and actual value for an inventory will be detected by a PIV. There are, of course, safeguards problems associated with measurement uncertainty that this does not capture, but there are also well-known strategies (e.g., attributes/variables measurements) for dealing with them.
19. If material from MIL A is normally processed into material that goes into MIL B, one would usually assume that A could be substituted for B, because material from A can always be fed to the process that produces the B material. If one assumes that material from A can be taken to an undeclared location and processed into a material form that is indistinguishable from B, this also qualifies as substitutable.
20. Of course in spent fuel we usually don't know exactly what the U or Pu content is, but safeguards really treats spent fuel as a separate species altogether.
21. The timing of the declarations of flows can be thought of as taking place on a frequent periodic basis. (Although, in the end, the only points in time that will really be important are those when PIVs occur.) Technically, data is, for each ordered pair of MILs, an amount and a species of nuclear material going from the first to the second at each time interval.
22. We assume that observed PIV value for the last inventory agreed with the then-book-inventory, otherwise there would have been a diversion detected.
23. The assumption of continuous monitoring can in many circumstances be loosened.
24. This definition specifically puts the monitoring point between two species of material. If the material on both sides of the monitoring point were identical (or fungible), measuring the flow would seem pointless -- unless, as in the case of an MMIL, one knows that the material cannot be simply moved back and forth past the monitoring point. There are actually two variants of the MFP concept, as explained in the footnote 28 to d) two paragraphs below.
25. It may be that there are other meaningful concepts of "flow verification," but the author cannot think of any. Recall earlier in this paper, when an inspector measures a cylinder of UF_6 presented as a "flow item" all he is really verifying is that there is a certain amount of UF_6 in an item in front of him, not that that material has irrevocably passed from one MBA to another.
26. In practice, although they are invisible in this description, there would be observations and anomalies associated with the operation of the MMILs and MFPs, which will involve C/S devices. These are absorbed into the last two bullets.
27. There are really two cases, depending upon the nature of the safeguards and the process. The <u>weak</u> MFP is as defined above. It does not prevent the MFP from being bypassed, so someone could sneak material into the process past the MFP and create the new species of material undetected; but he could not <u>over</u>-declare that flow without detection. A <u>strong</u> MFP would omit the phase "*at the designated process point*" so that the inspector knows how much material goes into the process and how much of the new species of material is created. A monitored shearing cell/dissolver/accountability tank at the input to a reprocessing plant we would usually assume to be strong. A feed monitor at the input to an enrichment plant, without additional monitoring to detect in-cascade feeding, would be weak.
28. The case of true random inspections is beyond the scope of this example.
29. For example see paragraph 4 of INFCIRC/153.
30. The game as described can be reduced to mathematics: the declared flows as a directed graph over the set of MILs; flow declarations are positive-valued functions on the edges of that graph with a time index, etc. One could thus ask for a general theorem that would characterize, for an arbitrarily complex fuel cycle, the necessary and sufficient conditions for an inspector win. Such an abstract proof is beyond the scope of the paper. What follows are arguments about necessary conditions – showing that under certain conditions, the inspector will lose, so they must be avoided. But in realistic cases the graphs involved are very simple (see Appendix), and one should be able to prove sufficiency (effectiveness) in specific real cases.
31. If the MFP is weak, we assume material can be moved undeclared from B into A bypassing the MFP, this amounts to understatement. It is also essentially a case of substitution of material, as in the first tic.
32. One might imagine circumstances where this might not pertain, but the conservative assumption is to assume it is always true.

33. In this model, there are three concepts of flow monitoring defined (weak MFP, strong MFP, and MMIL). It may be possible to conceive of other rigorously defined concepts of "effective flow monitoring," but they would have to take into account the problems inherent in the example earlier in this paper.
34. "Show" as in the proof logic presented in the next section.
35. It is only really necessary to assume that these anomalies are checked for at the four dates of the PIVs; using this assumption would not change the conclusion.
36. Diversion paths were originally conceived in the context of domestic safeguards, where they may be easier to use (see Reference 1), and then ported to international safeguards (Reference 2), subsequently morphing into different approaches (References 3 – 5).
37. In the case of the cascade, the inventory is assumed to be small and constant and therefore insignificant. The cascade inputs and outputs are monitored and there are measures in place to preclude undeclared feed or withdrawal. In the case of the power reactors, the assumption that everything is under effective C/S may be optimistic, but the issues of reactor safeguards (including measurement of spent fuel) are not the aim of this paper.
38. We could do without this assumption at the expense of making the example more complicated.
39. When we say "verified at the same time" it does not necessarily mean complete, simultaneous PIVs at all three places in actual practice. For example, one could require all three locations to be ready for a PIV and then pick one at random.

References

1. Murphey. W., et. al. 1974. *The Practicality of Diversion Path Analysis*, National Bureau of Standards NBSIR--74-524.
2. Pasternak, T., et.al. 1982. *Applications of IAEA Safeguards Effectiveness Assessment Methodology*, IAEA-SM--260/133.
3. Richter, B., et. al. 1991. Application of PASE for the Analysis of Possible Diversion Paths in a Final Disposal of Spent Nuclear Fuels, *ESARDA Symposium Proceedings.*
4. Elayat, H., et. al. 2006. Systems Analysis for Evaluation of Safeguards Effectiveness, *IAEA 2006 Safeguards Symposium,* IAEA-CN--148/38.
5. Pilat, J. 2001. *Possible Roles for the Integrated Safeguards Evaluation Methodology (ISEM),* LANL report LA-UR-01-3748.
6. Moran, B., J. Cooley, and E. Pujol. 2011. Making the IAEA Safeguards System Fully Information Driven, paper presented at the 33th ESARDA Annual Meeting, 16-20 May 2011, Budapest.

Expanding the Scope of Transparency to Strengthen the Nonproliferation Regime

Jonas Siegel
Center for International and Security Studies at Maryland (CISSM), School of Public Policy, University of Maryland, College Park, Maryland USA

Abstract

In the years since the 2000 Nuclear Nonproliferation Treaty (NPT) Review Conference, NPT nuclear weapons states have engaged in consequential transparency measures about their stockpiles of nuclear weapons and materials. The level of transparency thus far achieved, however, has proven uneven in terms of the types and amounts of information released and in terms of the frequency of those releases—and most importantly, has not contributed significantly to fulfillment of these states NPT commitments. Nuclear weapons states should reassess the scope of their transparency efforts to date and consider expanding the types of information that they reveal to provide international assurances and achieve gains in support of the nuclear nonproliferation regime. This paper identifies particular steps that these states could take to fulfill the desire for greater transparency that move beyond declarations of the number and status of nuclear weapons and nuclear materials. In particular, it focuses on how transparency can be expanded about the operational practices and protocols that govern the day-to-day management of their military nuclear materials—their warheads, weapons components, and material stockpiles—and how transparency in this area would contribute to fulfilling their disarmament and nonproliferation commitments.

Introduction

The Final Document from the 2000 Review Conference capped a decade during which global emphasis on transparency in nuclear materials and nuclear weapons had reached its high point and had already begun to recede. The Final Document nonetheless emphasized the need for greater transparency among NPT parties, particularly nuclear weapons state-parties to the treaty. "Increased transparency by the nuclear weapon states with regard to the nuclear weapons capabilities and the implementation of agreements pursuant to Article VI," was part of the thirteen "practical steps" that the parties agreed to pursue in the document. Increased transparency was also urged "as a voluntary confidence building measure to support further progress on nuclear disarmament."

In the years since the 2000 Nuclear Nonproliferation Treaty (NPT) Review Conference, nuclear weapons states have indeed engaged in consequential transparency measures. This transparency has primarily taken the form of making information available regarding their nuclear weapons and materials stockpiles. The United States, France, United Kingdom, and China have all made unilateral declarations about the sizes of their nuclear weapons arsenals—some in greater details than others. Similarly, the United Kingdom and the United States have released updated figures about the production of nuclear materials in their states, and all weapons states have continued to make information available about their plutonium holdings under INFCIRC/549 declarations. Additional information about the nuclear weapons and materials stockpiles of the United States and Russia were released as part of the START and New START treaties, and threat reduction initiatives such as the HEU purchase agreement and the plutonium management and disposition agreement.

The action plan developed at the 2010 NPT Review Conference attempted to stimulate further transparency from the nuclear weapons states. Indeed, the P5 process that was initiated prior to the 2010 conference took up the disarmament-related items from the action plan in an attempt to focus on them in a structured manner.

Despite this progress, the level of transparency thus far achieved by NPT nuclear weapons states has proven uneven in terms of the types and amounts of information released and in terms of the frequency of those releases. The most telling measure of weapons states' transparency efforts to date is the overwhelming dissatisfaction of NPT non-nuclear weapons states. In the run-up to the 2015 NPT Review Conference, representatives of non-nuclear weapons states and nongovernmental organizations around the world (including in nuclear weapons states) have repeatedly called for greater transparency from weapons states in pursuit of disarmament and nonproliferation objectives.[1]

Nuclear weapons states argue that greater transparency has run up against persistent concerns about the security and protection of nuclear warheads and materials, and against what weapon state governments deem to be the requirements of maintaining credible nuclear deterrence capabilities. While there is some credence to these concerns, nuclear weapons states should also consider reassessing the scope of their transparency efforts to-date and expanding the types of information that they could reveal to provide international assurances and achieve gains in support of the nuclear nonproliferation regime that have thus far proven elusive.

This paper identifies particular steps that nuclear weapons states could take to fulfill the desire for greater transparency that move beyond declarations of the number and status of nuclear weapons and special fissionable materials. In particular, it focuses on how nuclear weapons states could make publicly available information about the operational practices and protocols that govern the day-to-day management of their military nuclear materials—their warheads, weapons components, and stockpiles—and how transparency in this area would contribute to fulfilling their disarmament and nonproliferation commitments.

Nuclear Transparency, In Practice

Nuclear transparency most commonly involves the disclosure of previously unavailable information relating to the production and use of nuclear technologies and materials, but the concept also includes "the accessibility and reliability of such information."[2] Under this conception, transparency is often seen as a confidence building measure that produces "greater predictability with regard to the intentions and capabilities of states, thus facilitating mutual understanding, easing tensions, and reducing misperceptions."[3]

Not all states see nuclear transparency the same way, however. Some states see transparency as a way for others to gain a competitive advantage or manipulate international relations and are thus hesitant to engage in its practice.[4] Indeed, states more willing to engage in nuclear transparency than others have used calls for nuclear transparency as a means to draw attention to the hesitance of others to engage in transparency.

The intended and actual effects of transparency measures also differ according to the context in which they are pursued and in the details of their implementation. Many nuclear materials and weapons transparency measures, including some of those listed in the previous section, are voluntary, unilateral measures, but transparency can also be an element of a formal, multilateral or bilateral agreement and can contribute to the verification of formal commitments. Indeed, the agreement that has brought the broadest and most consistent amount of transparency into the use of nuclear materials and technologies is the NPT, a formal, legally binding agreement that requires non-nuclear weapons states to provide detailed and regular declarations about all of their nuclear facilities, materials, trade, etc.

Transparency measures are also distinguished by the parties involved. When states make information *publicly* available, they are often trying to facilitate understanding, reduce misperceptions and, provide assurances about their capabilities and intentions to a range of actors, other states, international bodies, the nongovernmental community, and the public at large. The public release of information could also be used to deliberately intimidate other states or to boost national pride. Other transparency measures include the revelation of information to intergovernmental authorities alone, as is the practice with IAEA safeguards agreements. Still other transparency measures, such as those that are related to bilateral arms control agreements, involve the sharing of information between states. In these two later cases, the amount of public transparency is limited.

Before suggesting how it is possible to broaden the scope of nuclear weapons state transparency efforts, this paper reviews several prominent efforts from the past fifteen years in which nuclear weapons states have tried to increase transparency. These overviews detail the measures' stated goals and their relative success in achieving them.

The NPT. In the direct context of the NPT, transparency primarily serves to ensure nuclear nonproliferation by allowing all states to have confidence that those states who foreswore developing nuclear weapons in joining the treaty are honoring that commitment. By making declarations, submitting to monitoring, and opening up facilities for inspections, an NPT signatory assures other states parties that they are not diverting nuclear material or technologies to the development of nuclear weapons.

The success of the NPT to date has rested in large part on the transparency non-nuclear weapons states have provided under the treaty. IAEA safeguards agreements are detailed documents that outline the specific types and frequency of reporting that are needed for each individual state to ensure compliance with the treaty. The level of detail and scope of safeguards agreements, including material accounting requirements and reports on facility design; the clarity of the ultimate goal that they serve—to ensure that non-weapons states don't divert nuclear materials or technologies for non-peaceful uses; and the ability of a third party (and other states) to assess the information made available all contribute to efficacy of the transparency requirements.

The five state parties designated as nuclear weapons states under the treaty provide some but relatively little transparency about their civilian nuclear facilities and materials under their treaty commitments. All of these states have voluntary offer agreements with the IAEA and make a range of facilities and materials available for safeguarding, but in practice, the IAEA safeguards relatively few facilities and materials in these countries. In addition, these states provide no formal transparency under the NPT regarding their military stockpiles of nuclear weapons and materials. In other words, the transparency that has traditionally resulted directly from the NPT has not supported weapons reductions and disarmament, despite the fact that the passage of the treaty hinged on the inclusion of both nonproliferation and disarmament commitments.

The historical limits on nuclear weapons states' transparency under the NPT contributed to calls prior to the 2000 NPT Review Conference for nuclear weapons states to engage in further transparency in support of their Article VI disarmament commitments.[5] While invoking nuclear weapons states' commitments under the NPT, the calls for transparency included in the Final Document from the 2000 Review Conference were vague and didn't have the legal force of treaty commitments. As such, the transparency that resulted—the unilateral public declarations of nuclear material production, of weapons stockpile size, and of weapons reductions—was limited and even held the potential to create confusion rather than clarity.

For instance, a May 2010 U.S. press release noted that the U.S. stockpile "consisted of 5,113 warheads," a number that included active warheads that were deployed on weapon systems; "responsive" warheads that could be deployed on short notice and serve as a strategic hedge; and inactive warheads, intact warheads stored at U.S. Defense Department installations that had their limited-lifetime components removed. A subsequent U.S. State Department release noted that, as of December 2009, 1,968 of this total were deployed strategic weapons. Of the remaining 3,145 weapons, it was unknown precisely how many were included in the "responsive" force, which could be deployed on short notice, and how many were inactive. Officials were also vague in describing that "several thousand additional nuclear weapons are currently retired and awaiting dismantlement."

Though the United States and the United Kingdom released information about their historical production of plutonium and HEU, including details about current holdings, this information was on the aggregate level. The United States recently updated its plutonium declaration, but it presented the same limitations as the initial declaration.

New START. Since its entry into force in February 2011, the New START treaty has facilitated additional transparency between the United States and the Russian Federation, as the two nations reduce their deployed warheads and launchers, and their non-deployed launchers to treaty limits. Most of the transparency brought about by the treaty, however, is limited to the exchange of information *between* the two countries. While the detailed data exchanges and notifications spelled out by the treaty provide assurances and contribute to the overall confidence of the two parties that the other is complying with its treaty commitments (more than 8,000 notifications of changes to data kept under the treaty have been sent between the two states as of early 2015), this kind of transparency has limited value to the other nuclear weapons states and to non-weapons state-parties to the NPT since they don't have access to the data and have to merely take the United States and Russia at their word.

The United States and, to a lesser extent, Russia have released aggregate data about the items limited by New START giving all states a general sense for how they are progressing toward the treaty's goals. Yet, only Russian officials are verifying U.S. reductions, and vice versa. And little to no information is made publicly available about the specific procedures that Russia and the United States use to verify the limits imposed by the treaty, not to mention how these states manage or dismantle their remaining weapons, launchers, and facilities—elements outside the scope of the treaty.

While the verification processes that the United States and Russia use under this treaty have been sufficient to sustain the treaty since its entry into force, the transparency that has resulted from the treaty has done little to assuage the concerns of the other nuclear weapons states or to assure non-nuclear weapons states that disarmament commitments are being pursued with vigor. Understanding the specific verification mechanisms under the treaty and having access to all of the data exchanged by the parties could in theory provide greater assurance that the limits imposed by the treaty were indeed being put into place, but this wouldn't provide any more assurance that nondeployed nuclear warheads are secure, being dismantled, etc. than the incomplete statements already made by these governments.

The P5 Process. In 2009, the British government hosted the first of several meetings of the "P5 Process" that was intended to allow the five NPT-sanctioned nuclear weapons states to review and devise the technical steps that would be needed to achieve and verify nuclear weapons disarmament. After the 2010 Review Conference, the P5 Process agenda evolved to include disarmament-related items from the conference's action plan, including its call for all states to "submit regular reports" on their implementation of the action plan (Action 20) and for weapons states to agree to "a standard reporting form" for information regarding their nuclear weapons and nuclear materials stockpiles, policies, and related activities outlined in the action plan (Action 21). This latter action item also encouraged these states "to determine the appropriate reporting intervals for the purpose of voluntarily providing information without prejudice to national security."

The P5 Process has involved five subsequent meetings since its inauguration in 2009, the last of which took place in February 2015. While officials from the P5 Process have reached agreement about categories of information to be included on a standard reporting form (e.g., information regarding nuclear doctrines, arms control and disarmament activities, information on weapons arsenals and fissile materials), the process doesn't appear to have produced sufficient consensus about the specific types of information that could and should be included in these categories, which means reporting will "not be uniform" in either its contents and its frequency of availability.[6] It's noteworthy that the categories on the standard reporting form are also meant to limit the amount of quantitative information included in the reports.[7]

Despite the limitations of the standard reporting form, all five NPT nuclear weapons states submitted reports to the NPT Preparatory Committee in an effort to comply with the contents of the disarmament-related action items. A review of the contents of each weapons state's report reveals that they were primarily symbolic in nature and contained little in the way of new information about, for example, nuclear weapons doctrine, warhead or material stockpiles, or nuclear security and nonproliferation policies and procedures.[8]

The failure of the P5 states to agree on the detailed contents of a standard reporting form does not inspire confidence and might even draw unwanted attention to the inability or reticence of the weapons states to make tangible progress toward their disarmament commitments at the upcoming review conference. The reasons for the lack of positive impact from this P5 project are manifold, but a significant reason is the lack of clarity about what actions would constitute progress transparency in pursuit of disarmament. Without a clear objective to pursue, how could it be achieved? This could be because weapons states' transparency is itself only a single item on the larger "thirteen steps" agenda. It also could be because non-nuclear weapons states and nongovernmental organizations haven't identified the specific types of transparency that would provide sufficient assurance that nuclear weapons states are fully committed to holding up their part of the NPT bargain.

Expanding the Scope of Weapons State Transparency

In working papers submitted to the 2015 NPT Preparatory Committee, members of the Nonproliferation and Disarmament Initiative, an aligned group of states, emphasized the "sporadic and informal" nature of nuclear weapons state reporting on nuclear weapons and materials in response to calls for transparency in the final documents of previous NPT review conferences.[9] To spur further action from the nuclear weapons states, the initiative devised its own draft standard reporting form. Several nongovernmental initiatives have put forward similarly oriented draft reporting forms for consideration.[10]

While nuclear weapons states can and should do more to make available detailed and continuously updated information about their stockpiles of nuclear weapons and nuclear materials as a means to fulfill their disarmament commitments and to reassure one another, it is also worth reassessing the scope of transparency efforts to date in an attempt to achieve gains in support of nuclear disarmament that have thus far proven elusive. Transparency about *how* warheads and materials are managed and accounted for could better provide assurances to non-nuclear weapons states and weapons states that announced changes in nuclear policy or nuclear posture are indeed being pursued and that the control and security of warheads and materials at every step of the weapons production and dismantlement process is assured so as to avoid accidental or unauthorized access. This type of transparency could give credibility to the cause of disarmament and provide short-term gains in nuclear security and nonproliferation, as well.

Starting in 2011, the Center for International and Security Studies at Maryland (CISSM) led a study to examine the nuclear material accounting practices of nuclear weapons states and non-nuclear weapons states.[11] A foundational element of nuclear safeguards, nuclear material accounting is also a key aspect of broader transparency initiatives in that declarations about nuclear warheads and materials rely on material accounting systems and reports, both past and present-day, to ensure that the information contained within reporting meets standards of accuracy and completeness. Absent standards for how material accounting is conducted and evidence that operations meet those standards, the information made available to other parties or the public as a whole is unlikely to provide reassurance or reduce confusion and misperception.

The CISSM study found that the nuclear material accounting standards and practices for civilian materials within nuclear weapons states are uneven, and some differ in important ways from material accounting requirements outlined in the model IAEA safeguards agreement. For instance, experts question whether China or Russia have accurate baselines of nuclear materials (based on material measurements) that have been produced and are presently held in their nuclear complexes.[12] The requirements for reporting changes in material inventories to national-level material accounting systems and for conducting physical inventories of all materials vary between several of the weapons states and IAEA safeguards requirements. More importantly for the purposes of this paper, the study found that little to no information is publicly available about material management and accounting practices for these states' military nuclear materials, including those materials assigned for use in naval reactors and those materials assigned for use (or in use) in nuclear warheads of all statuses.[13]

Nuclear weapons states typically justify their reluctance (or refusal) to reveal how they account for or otherwise manage military materials and warheads by arguing that information about their management has the potential to make them vulnerable to theft or attack, or to introduce instability into deterrence relationships. (Not surprisingly, the same argument is made about details regarding material and warhead stockpiles, which is why transparency on these stockpiles has been so uneven and infrequent since 2000.) While there is undoubtedly some truth to this claim, and transparency doesn't always benefit nuclear security or nonproliferation goals, there has not been a thorough discussion about what types of information *can* be revealed without negatively affecting international security. Nor has there been a thorough discussion about under what arrangements—who would be the recipient of such information, how frequently would they receive it, etc.—such transparency could be achieved.

Would revealing information about how nuclear material and warhead stockpiles are managed and accounted for affect the security of the materials or deterrence relationships in the same way as revealing information about the materials and warheads themselves? Certain operational details about how physical access to warheads and materials is controlled or how materials are transported could certainly compromise security. Other information about warhead maintenance schedules and processes, the process through which warheads are recalled from operational status or deployed, or the specific movements of fissile components of warheads, could conceivably complicate current deterrence relationships.

Yet other forms of process transparency could be accomplished with seemingly little to no effect on security or deterrence. It is hard to imagine how general information about physical inventory practices for warheads and nuclear materials along the continuum of statuses, how changes in these inventories are reported, what types of systems are used to store the information about these stockpiles, how these systems are audited and how often, etc. would affect the physical security of the materials and warheads or deterrence relationships. The revelation of lax standards and practices in these areas would be embarrassing to government officials, but that is not the same as suggesting they could affect security and deterrence. An agreement to share this type of information with a delayed implementation date would create incentives to improve accounting and security practices before reporting begins. Furthermore, if this type of process information is controlled adequately—e.g., shared only with other weapons states or with a select grouping of non-weapons states—the potential for unintended effects is diminished.

One specific area ripe for further transparency is the warhead dismantlement process and the storage, processing and accounting of the fissile material components of these weapons. All NPT nuclear weapons states have reduced their operational stockpiles of nuclear warheads, but there is little clarity about what happens to these warheads or their fissile material components next. What factors dictate rates of dismantlement? Are states meeting their dismantlement plans? How are these non-operational warheads and nuclear components accounted for and secured? What standards are in place to ensure their nondiversion to state or non-state actors? Are these standards regularly met?

Previous efforts to establish transparency regarding the dismantlement of nuclear warheads have focused on ensuring that warheads slated for dismantlement are indeed warheads removed from operational stockpiles and that specific weapons components are indeed removed from the warheads in question.[14] In other words, these forms of transparency were meant to be a part of a verification regime that accompanied a formal weapons reduction agreement. While this would be a desirable form of transparency under those circumstances, a more general, informal form of transparency could help to demonstrate weapons states' progress on their NPT disarmament commitments short of additional formal arms reduction agreements.

For instance, nuclear weapons states could declare in general terms how they structure and manage the warhead dismantlement process: How long does the process generally take? How are warheads accounted for and secured while they await dismantlement? What, if any, steps are taken that would slow the process of redeploying these warheads? To what standards are all of these processes held and how frequently are they met? The same types of information can also be made available about materials removed from warheads but still in the form of weapons components. If a state has committed certain warheads to dismantlement, then providing some information about this process and providing some international assurance of how it will be completed could clearly communicate that it is committed to preparing for, if not achieving, stated weapons reductions. Other states might ultimately seek additional evidence to confirm that warheads slated for dismantlement are indeed dismantled, but that would involve a form of transparency that is more like that found within specific verification measures of formal treaties.

The Potential Effects of Process Transparency

While it may be possible to identify types of information about nuclear weapons states military nuclear enterprises whose revelation would not increase threats to their security or negatively affect deterrence relationships, the question remains whether transparency along the lines suggested above would adequately answer calls for nuclear weapons state progress on their NPT disarmament commitments.

As explored in the previous section, transparency about how military nuclear materials and nuclear warheads are managed could help to communicate a state's intention to follow through on weapons reductions. It also holds the potential to make the application of international safeguards less discriminatory. By demonstrating a willingness to share information about nuclear warheads and materials that is similar in type to the information that is routinely made available as part of non-nuclear weapons states' IAEA safeguards commitments, weapons states could contribute to the fulfillment of Article VI commitments. Coupled with weapons states' commitments to subject their civilian materials to the requirements of model IAEA safeguards, this commitment could significantly reinforce the foundation of the NPT.

Counter to prevailing concern, this type of transparency could also reduce the overall risk of proliferation or theft of existing military materials and warheads. Before engaging in transparency about the processes that are used to manage warheads and nuclear materials, weapons states would be likely to review them internally and ensure strict compliance. Making available information about compliance with security standards, at least whether operations meet standards or not, would also motivate weapons states. Finally, enacting process transparency would ensure the development of a capability that is a prerequisite for the significant reductions of warheads and the realignment of policies that Article VI aims to achieve in the long run.

In December 2013, Austrian diplomat Alexander Kmentt pointed to the possibility that divergent points of view on what would constitute significant progress on Article VI commitments could place "too much stress on the credibility and cohesion of the NPT" for it to survive.[15] The relative lack of perceived progress that nuclear weapons states have made in response to calls for greater transparency about their weapons programs and policies contributes to this divergence of views. Yet it also presents weapons states an opportunity to rethink how they can go about pursuing these commitments in a manner that both preserves their national prerogatives and fulfills their obligations to their international partners.

Keywords

Nuclear nonproliferation, disarmament, transparency, safeguards, NPT, IAEA, nuclear weapons, nuclear materials

Jonas Siegel is a project manager at the Center for International and Security Studies at Maryland (CISSM), School of Public Policy, University of Maryland. He was the lead author of Comprehensive Nuclear Material Accounting *(2014). Siegel received his master's degree in journalism in 2000 from the University of Illinois.*

References

1. See "Increased Transparency in the Disarmament Process," a working paper submitted by the members of the Nonproliferation and Disarmament Initiative to the 2014 Preparatory Committee Meeting for the 2015 NPT Review Conference, March 19, 2014, NPT/CONF.2015/PC.III/WP.10; Deepti Choubey, "Are New Nuclear Bargains Attainable?" Report of the Carnegie Endowment for International Peace," 2008; "Statement by H.E. Don MacKay, Permanent Representative to the United Nations in Geneva," statement to the 2nd Preparatory Committee Meeting for the 2010 NPT Review Conference, April 30, 2008; Bill Richardson et al., "Universal Transparency: A Goal for the U.S. at the 2012 Security Summit," *Arms Control Today*, January/February 2011, pp. 8-13.
2. Zarimpas, N. 2003. "Introduction," in Nicholas Zarimpas (ed.), *Transparency in Nuclear Warheads and Materials: The Political and Technical Dimensions*, Oxford, UK: Oxford University Press, 2003.
3. Ibid.
4. See: Li Bin, "China and Nuclear Transparency," in Nicholas Zarimpas (ed.), *Transparency in Nuclear Warheads and Materials: The Political and Technical Dimensions* (Oxford, UK: Oxford University Press, 2003), p. 55. Russian concerns about nuclear transparency have surfaced in discussions about tactical nuclear weapons, as well as in regards to nuclear material production. See: Alexander Pikayev, "Transparency and Security in Russian-U.S. Nuclear Relations," Nicholas Zarimpas (ed.), *Transparency in Nuclear Warheads and Materials: The Political and Technical Dimensions* (Oxford, UK: Oxford University Press, 2003) and in Dmitry Kovchegin, "Developing a Nuclear Material Control and Accounting System in Russia," CISSM Working Paper, December 2013, available at www.cissm.umd.edu.
5. A call for greater nuclear weapons state transparency was presented in the European Union's Common Position paper prepared for the 2000 NPT Review Conference, as well as by a review conference working papers submitted by the New Agenda Coalition and the "NATO-5" group, which included Belgium, Germany, Italy, the Netherlands, and Norway).
6. Mukhatzhanova, G. 2014. Implementation of the Conclusions and Recommendations for Follow-on Actions Adopted at the 2010 NPT Review Conference, Disarmament Actions 1-22: *2014 Monitoring Report*, Center for Nonproliferation Studies, April 2014.
7. Berger, A. 2014. "The P5 Nuclear Dialogue: Five Years On," an occasional paper of the Royal United Services Institute (RUSI), July 2014.
8. Ibid.
9. "Increased Transparency in Nuclear Disarmament," March 19, 2014; "Transparency of Nuclear Weapons: The Nonproliferation and Disarmament Initiative," a working paper submitted by Australia, Canada, Chile, Germany, Japan, Mexico, the Netherlands, Poland, Turkey, and the United Arab Emirates, to the 2012 Preparatory Committee Meeting for the 2015 NPT Review Conference, April 20, 2012; NPT/CONF.2015/PC.I/WP.12.
10. Nuclear Threat Initiative. 2013. *Verifying Baseline Declarations of Nuclear Warheads and Materials*, a single volume from a series published as part of the Innovating Verification: New Tools & New Actors to Reduce Nuclear Risks, July 2014; International Panel on Fissile Materials, Increasing Transparency of Nuclear-warhead and Fissile-material Stocks as a Step toward Disarmament, Proposals for the NPT PrepCom, Geneva, April 24, 2013.
11. Jonas Siegel, John Steinbruner, Nancy Gallagher, *Comprehensive Nuclear Material Accounting*, CISSM Monograph, March 2014.
12. Ibid, p. 41; Kovchegin, Developing a Nuclear Material Control and Accounting System in Russia.
13. Ibid., p. 45.
14. The most prominent effort focused on this area was the IAEA Trilateral Initiative, which in the words of its head James O'Shea, was an effort to develop a verification system under which Russia and the United States could submit classified forms of weapons-origin fissile material to International Atomic Energy Agency (IAEA) verification and monitoring in an irreversible manner and for an indefi-

nite period of time. Other work was done on this issue in direct support of prospective nuclear arms reduction agreements, see: James Goodby, Transparency and Irreversibility in Nuclear Warhead Dismantlement, in Harold A. Feiveson (ed.), *The Nuclear Turning Point: A Blueprint for Deep Cuts and De-Alerting of Nuclear Weapons* Washington, DC: The Brookings Institution Press, 1999, pp. 171-192.

15. Kmentt, A. 2013. How Divergent Views on Nuclear Disarmament Threaten the NPT, *Arms Control Today*.

Safeguarding Uranium Production and Export–Conventional and Non-Conventional Resources

Craig Everton
Australian Safeguards and Non-Proliferation Office, Barton, Australia

Abstract
All nuclear material in both civil and military applications originated at some point from uranium mining and production; followed by various processing steps to purify and condition the uranium for use. It is clear that the most robust of controls must be on the stages of the nuclear fuel cycle where fissile material suitable for the development of a nuclear explosive device can be produced. Controls at this stage of the nuclear fuel cycle are essential to maintaining international confidence in the compliance of states with their nonproliferation commitments. But what are the appropriate levels of control at the very start of the fuel cycle, i.e., uranium mining and production? This paper will consider this question both from the perspective of IAEA safeguards and of national regulatory controls on this industry.

Introduction
The maxim the International Atomic Energy Agency (IAEA) applies to its compliance monitoring relationship with states is "trust but verify." It maintains a respectful relationship with states but must also maintain credible verification mechanisms to preserve international confidence in the compliance of states with nonproliferation commitments. With this in mind, the working hypothesis for its verification system is that the diversion or acquisition of nuclear material to a nuclear weapon program cannot be discounted and so a risk-based system is put in place to test this hypothesis.

Following such a risk-based approach, safeguards are necessarily prioritised on stages of the nuclear fuel cycle with the highest intrinsic potential for the diversion of nuclear material to military uses. The principle focus of IAEA safeguards verification activities therefore is the later stages of the nuclear fuel cycle; i.e., enrichment, reprocessing, fuel fabrication, nuclear power, and nuclear research reactors. This prioritization is also underpinned by expectations built into comprehensive safeguards agreements (modeled on IAEA document INFCIRC/153 (corrected)). Paragraph 6 of INFCIRC/153 includes the provisions that:

> "In order to ensure optimum cost effectiveness, use should be made, for example, of such means as: … (c) Concentration of verification procedures on those stages in the nuclear fuel cycle involving the production, processing, use or storage of nuclear material from which nuclear weapons or other nuclear explosive devices could readily be made, and minimization of verification procedures in respect of other nuclear material, on condition that this does not hamper the Agency in applying safeguards under the Agreement"

There are other provisions in INFCIRC/153 that also bear on how the IAEA applies safeguards to uranium mining and production. Paragraphs 33 and 34 make up a small section of INFCIRC/153 titled "Starting Point of Safeguards." Paragraph 33 sets a lesser threshold for safeguards whereby "safeguards shall not apply…to material in mining or ore processing activities." And paragraph 34(c) defines the point at which nuclear material has been processed to a level where the full suite of safeguards measures applies:

> "When any nuclear material of a composition and purity suitable for fuel fabrication or for being isotopically enriched leaves the plant or the process stage in which it has been produced…the nuclear material shall become subject to the other safeguards procedures specified in the Agreement."

Paragraph 34(c) has generally been interpreted as applying from some point in the conversion stages of the fuel cycle where uranium ore concentrates are converted to uranium hexafluoride. Before this stage of the fuel cycle, nuclear material in the form of uranium ore concentrates (as exported by major uranium producers such as Kazakhstan, Canada, Australia and Namibia) is referred to in safeguards parlance as "pre-34(c) material."[1]

It is important to appreciate that between ore processing activities (paragraph 33) and when the nuclear material reaches the composition and purity thresholds in paragraph 34(c) that some safeguards measures do still apply. Paragraphs 34(a) and 34(b) oblige the state to report to the IAEA exports and imports of any nuclear material intended for nuclear use that has not reached the composition and purity outlined in paragraph 34(c).[2] What this usually means in practice is the regular reporting of exports and imports of uranium ore concentrates.

Under INFCIRC/153 therefore, the IAEA's oversight of uranium production and export is typically limited to import and export data. As will be discussed later, this was intentional in the drafting of paragraph 34. With the introduction of the Additional Protocol[3] in the late 1990s the IAEA was given more oversight of the earliest stage of the fuel cycle through provisions providing rights to information on, and access to, uranium mines and concentration plants. The Additional Protocol does not however provide for the full accounting and control procedures on uranium production that are found in INFCIRC/153 for all the other stages of the nuclear fuel cycle.

As has been described in this section, INFCIRC/153 guides how the IAEA should prioritise its verification activities to the stages of the fuel cycle where intrinsic risks are greater. This prioritization of effort is self-evident given the IAEA has every stage of the fuel cycle in multiple states to concern itself with and only finite resources. That being said, the constraints on the IAEA in INFCIRC/153 should not limit how states apply their own regulatory controls on their own uranium production and export activities. For one thing, to maintain international confidence in how uranium resources are being used, and to maintain the public confidence that acts as a "social licence" for commercial endeavours in uranium production, a prudent, risk-based level of state regulatory control is necessary. Furthermore, regulatory control is required under INFCIRC/153, as will be discussed later.

This paper will now provide a snapshot of some of the debate that occurred during the negotiations of INFCIRC/153[4] followed by Australia's perspective and practice of what is a reasonable level of state regulation and control on uranium mining and production.

INFCIRC/153 Negotiating History

In April 1970, the IAEA Board of Governors adopted a resolution establishing a committee (known as Committee 22) on "the Agency's safeguards responsibilities in the light of the *Treaty on the Nonproliferation of Nuclear Weapons*" (GOV/INF/222). Committee 22's task was to consider the content of the safeguards agreement required by the (then new) *Treaty on the Non-Proliferation of Nuclear Weapons* (NPT). Committee 22 was composed of representatives from around fifty IAEA member states and held some eighty-two meetings from 1970 to 1971 to draft what would become INFCIRC/153, for the consideration and approval by the IAEA Board of Governors.

As mentioned in Introduction section above, the paragraphs in INFCIRC/153 of most relevance to uranium mining and production are paragraphs 33 and 34. During the negotiations of INFCIRC/153 there was considerable debate on the following areas related to uranium production:

- Where should safeguards measures apply beyond mining and ore processing?
- What measures should apply to the import and export of source material[5]?
- How should source material be defined?

Committee 22 understood that accountancy and control obligations had to start from a sensibly defined process stage or uranium and thorium concentration threshold, as it was clearly not practical to account for and control uranium or thorium in the form of ore or in trace amounts in mineral concentrates used in non-nuclear industries. It was also determined early in the negotiations that while some uranium and thorium-bearing materials would not be subject to full safeguards, the import and export of such material should at the very least be reported to the IAEA. The main contributors to discussions on this were Australia, Canada, Finland, West Germany, Hungary, South Africa, the UK, and the U.S., many of whom had uranium mining interests.

Paragraph 33: "safeguards shall not apply…to material in mining or ore processing activities."

Early on in the negotiations several countries made it clear they were opposed to safeguards applying to ore or ore processing activities. There was general agreement amongst delegates on this point. It was noted for example that the IAEA's safeguards system at that time (as described in IAEA document INFCIRC/66/Rev.2) excluded mines or ore-processing plants. As such, the adoption of the text of paragraph 33 was relatively straightforward. The debate on this paragraph does not appear to have considered how to treat the product of ore processing (as distinct from material in the processing activity itself) in circumstances where the product approaches the sorts of purities contemplated by paragraph 34(c).

Paragraph 34(a): "When ***any material*** *containing uranium or thorium which has not reached the stage of the nuclear fuel* *cycle described in [34(c)] is…exported to a non-nuclear weapon state, the state shall inform the Agency of its quantity, composition and destination, unless the material is exported for specifically non-nuclear purposes" (emphasis added).*

This paragraph relates to the reporting of exports of pre-34(c) nuclear material, i.e., raw material such as uranium ore concentrates. Such material was not considered to be of a suitable composition and purity to warrant the application of the full suite of safeguards measures in INFCIRC/153, but because it can be feed material for subsequent stages of the fuel cycle, it was considered important that the IAEA at least have information on exports and imports. While this paragraph is typically used only for the reporting of exports of uranium ore concentrates, it does in fact apply to "any material" containing even trace quantities of uranium or thorium (e.g., phosphates, mineral sands, coal, tantalum concentrates) if such material is exported for nuclear purposes.

During the negotiations there were differing views on reporting of exports, between those who wanted reporting on the export of all material containing uranium or thorium (irrespective of intended use); those who wanted reporting to start where source material is processed to special fissionable material (i.e., no reporting on exports of uranium ore concentrates); and, those who wanted export reporting to be conditioned on whether the export was for nuclear purposes.

In response to the proposal for reporting on all source material exports, several states (e.g., Australia, South Africa, UK, and Canada) raised the potential impost on non-nuclear industries such as mineral sands and phosphate export industries. These commodities contain trace (around 100s of ppm) but extractable quantities of uranium but were not exported for nuclear purposes, and not considered economically viable sources of uranium. Other states raised the question that if paragraph 34(a) applied only to exports for nuclear purposes, then how should the IAEA and the receiving state interpret the absence of an export report.

The negotiations ultimately coalesced in the middle, based on a Finnish proposal[6] premised on nuclear use. The compromise that resulted was to build into 34(a) a *presumption of notifications* of exports ("when any material containing uranium or thorium…is exported to a non-nuclear weapon state, the state shall inform the Agency"), with non-notifications ("unless the material is exported for specifically non-nuclear purposes") being the exception.

Paragraph 34(b): "When any material containing uranium or thorium which has not reached the stage of the nuclear fuel cycle described [34(c)] is imported, the state shall inform the Agency of its quantity and composition, unless the material is imported for specifically non-nuclear purposes".

This is the import-reporting mirror to the export-reporting paragraph 34(a) and was not the subject of any separate or distinct negotiations from that on paragraph 34(a).

Paragraph 34(c): When any nuclear material of a composition and purity suitable for fuel fabrication or for being isotopically enriched leaves the plant or the process stage in which it has been produced,…the nuclear material shall become subject to the other safeguards procedures specified in the Agreement.

This paragraph is what is commonly referred to in the safeguards community as "the starting point of safeguards." However, this is a somewhat misleading description; a more accurate characterization would be to call this the starting point of *full* safeguards. Paragraph 34(c) defines the point at which nuclear material becomes subject to the full suite of accountancy, control, reporting, and inspection provisions in INFCIRC/153. The reason for the qualification "full," is that some safeguards still do apply to nuclear material that has not yet reached the compositions and purity outlined in paragraph 34(c); for example, the paragraph 34(a)/(b) reporting of exports and imports. Another example is the paragraph 7 requirement for states to establish and maintain a system of accountancy and control of nuclear material. This system should apply sufficient control on pre-34(c) material such as uranium ore concentrates to ensure states can report under paragraphs 34(a) and 34(b) if required.

During the negotiations of INFCIRC/153 there was lengthy debate over whether the starting point of safeguards should be: (a) inside the facility where the material reaches a certain state of nuclear purity; (b) when the material leaves such a facility; or (c) only when nuclear material is introduced into facilities that produce special fissionable material (e.g. enrichment facilities). The third proposal was quickly dismissed as the NPT requires safeguards to be applied to all source and special fissionable material, so stages of the fuel cycle handling only source material must be subject to safeguards.

The debate began with a discussion on uranium concentration thresholds for defining when full safeguards apply, and the IAEA Secretariat proposed the following definition:

> "…safeguards shall start to be applied in respect of uranium or thorium introduced into the fuel cycle from the point where a sample, representative of the production stream, contains more than 95 percent of U_3O_8 or ThO_2, by

weight, after conversion to oxide and heating in air at 850° to constant weight. It should further be provided that if, in a concentration or processing plant, uranium or thorium reaches this concentration in the middle of the process rather than at the end, safeguards shall begin with the next material balance area after this concentration has been obtained." (GOV/COM.22/62).

This proposal was not favoured by several in Committee 22, with the U.S. delegation observing that this definition would have divided the uranium production industry into two groups—those covered by safeguards and those not—which would have created an inequity in regulatory controls in a competitive industry. Another consideration was the complication of how to treat uranium or thorium where ore processing and concentration processes were combined. After much debate, the formulation for the starting point of safeguards came down in the end in favour of those advocating it start with the product of conversion plants, rather than a concentration-based definition. The final text of 34(c) includes a balance of considerations of composition, purity, and fuel cycle stage. The negotiating record does not appear to consider scenarios where a uranium production plant produces high purity uranium ore concentrates, but it is noteworthy that one consideration by Committee 22 in not favouring a quantitative concentration threshold approach was the importance of maintaining equity across the industry on safeguards obligations.

For the first thirty years after INFCIRC/153 was adopted the IAEA had been applying safeguards at the output of conversion plants. However, in 2003 the IAEA introduced a new policy paper, "Policy Paper 18: Safeguards Measures Applicable in Conversion Plants Processing Natural Uranium," under which safeguards implementation was brought forward to earlier parts of the conversion stage where purified uranyl nitrate is produced. It is interesting to note that allowing for flexibility in determining the point at which full safeguards apply was recognized during the negotiations of INFCIRC/153. In summarizing the balance of considerations in paragraph 34(c) of composition, purity, and fuel cycle stage, the U.S. delegation noted that: "those criteria could be modified in the future in order to allow for advances in technology. For example, it was possible that materials other than those just mentioned [uranium hexafluoride, metallic uranium, and uranium oxide] would constitute the starting point for the enrichment or fuel fabrication process." (GOV/COM.22/OR.60)

Surveying the Industry—Conventional and Unconventional Uranium Resources

Conventional Uranium Resources

Uranium resources[7] can be characterized under two categories, conventional and unconventional. Conventional resources are those from which uranium is recoverable as a primary product, a co-product, or an important by-product. Typically, the cut-off grade for conventional resources is about 500ppm of uranium, but this varies with the spot price for uranium. According to the joint OECD Nuclear Energy Agency and IAEA publication, *Uranium 2014: Resource, Production and Demand* (known as the "The Red Book"),[3] the estimate of the world's total identified uranium resources (reasonably assured resources + inferred resources) extractable at under US$130/kgU is 5,902,900 tonnes. The uranium needs of the civil nuclear industry (approx. 59,000 tonnes in 2012) are met by a small number of countries, with about 80 percent of world production coming from five countries, Australia, Canada, Kazakhstan, Namibia, and Niger.

Unconventional Uranium Resources

The majority of the nuclear industry's uranium needs are met by mining operations run by large international companies accountable to several government regulatory authorities and to international shareholders, so information about production, capacity, forward planning, etc. is readily available to the public and the IAEA. These governance arrangements can provide an additional level of confidence to the international community that these mines are being used consistent with nonproliferation commitments. The level of information about unconventional uranium resources however is not always as clear.

Unconventional resources are resources from which uranium is only recoverable as a minor by-product, and are not generally considered economically viable sources of uranium. Examples include phosphates, tantalum and copper concentrates, mineral sands, and monazite. Uranium concentrations vary considerably but are typically of the order of 100s of ppm. Coal fly ash can even be considered an unconventional resource of uranium, even though uranium concentrations are low (around 10-40ppm). Estimates of the global quantity of unconventional uranium resources vary considerably. The 2014 Red Book states that resources associated with marine and phosphorite deposits could be almost 9 million tonnes of uranium held in only four countries: Jordan, Mexico, Morocco, and the United States. The Red Book also notes that some estimates put the world's total around 22 million tonnes; a much larger figure than for conventional resources.

There is a large production and export industry in unconventional resources, almost exclusively for non-nuclear use with no extraction of uranium. The resources are exploited for rare earths for the electronics industry, phosphates for agriculture, mineral sands for ceramic tiles etc., but very rarely for nuclear purposes.

Given unconventional resources make up only a tiny proportion of the uranium supply for the civil nuclear power industry, why is there a need to have controls over such materials? There are three main reasons:

- Given the generally tight government and corporate governance oversight of conventional uranium production around the world, proliferators could look for supplies of uranium outside of the standard commercial arrangements. For each of the unconventional resources listed above, there have been examples of uranium being extracted for nuclear purposes in the past.
- Unconventional uranium resources will likely become more economically viable in the future if the uranium spot price increases and/or if new technologies that make extraction more efficient.
- There are treaty requirements that can relate to exports of unconventional uranium resources. As outlined above, INFCIRC/153 requires states to report to the IAEA the export of *any* uranium or thorium *unless* for specifically non-nuclear purposes. Also, there are UN Security Council Resolutions that restrict supply of uranium to some states.

It is incumbent on states that may export uranium-bearing ores or concentrates to apply prudent controls to be able to evaluate the risk of uranium being extracted for nuclear purposes and if so, to apply appropriate controls on such exports. This should be done in a measured manner, including through raising awareness with potentially effected industries, as it is also important to minimise impacts on legitimate industries and exports.

Prudent Controls on Uranium Export—Australia's Approach

Effective regulation of uranium production and export is not just a matter of meeting treaty obligations; it is also in the national interest and the industry's interest. Firstly, while the proliferation, security, and radiological health risks associated with uranium ore concentrates are very low, nonetheless there is a small risk that should be managed with appropriate controls. Furthermore, given the public profile of uranium, maintaining public confidence and trust requires greater care than many other industries that may have comparable or higher risk profiles. As such, the interests of both governments and the industry are best served by being able to demonstrate that there are robust and effective regulatory systems and controls.

The following will outline Australia's approach to regulatory controls on uranium production and export. This is not to suggest that this is the only regulatory model—other producer countries also have models to achieve the same objective—but it serves as an illustrative example of the approach taken by one major producer.[4]

Australia has substantial uranium resources and currently has four operating uranium mines. Australia has around 32 percent of the world's reasonably assured resources extractable for under US$130 per kg (based on 2014 Red Book figures) and is the world's third largest uranium exporter behind Kazakhstan and Canada. Australia produces around 10-15 percent of the international civil nuclear industry's demand for uranium. Australia also has a substantial production and export industry for uranium-bearing ores and concentrates such as mineral sands, tantalum concentrates, and monazite, exported for non-nuclear purposes. A significant proportion of Australia's export of mineral sands and other ores and concentrates have uranium and thorium concentrations over 500ppm combined.

Under the Commonwealth *Customs (Prohibited Exports) Regulations 1958* the export of uranium or thorium requires an export permission, issued by the relevant minister or an authorized person in the minister's department. The Regulations cover conventional resources such as uranium ore concentrates as well as unconventional resources. The Regulations do this by introducing a *modified definition of source material* under Schedule 7 in relation to "Goods the exportation of which is prohibited without the permission of the Minister…or an authorized person." The definition of source material of relevance to unconventional uranium resources is:

- uranium containing the mixture of isotopes occurring in nature;
- any [uranium]…in the form of metal, alloy, chemical compound, ore or concentrate, including monazite, tantalum concentrates and tantalum glass; <u>but not including</u>:
- any ore or concentrate: containing less than 0.05 percent by weight of [uranium or thorium]…or of a combination of those materials; and
- not excluded…by a list or document formulated by [the Minister].

In summary, any ore or concentrate with a combined uranium and thorium concentration of over 0.05 percent (500ppm) requires an export permission irrespective of whether it is for nuclear or non-nuclear end-use. And if a circumstance were to arise where it is considered necessary to apply export controls on a commodity with uranium and thorium concentrations below this threshold, the minister may issue an exception bringing it under the Regulations.

For exports of uranium ore concentrates, long-standing Australian policy in place since the late 1970s requires that uranium only be supplied to countries within Australia's network of bilateral nuclear cooperation agreements. These agreements apply strict safeguards and reporting requirement designed to ensure that Australian obligated nuclear material remains in exclusively peaceful use and in accordance with all conditions in the agreement. Australia currently has twenty-three such agreements in force covering forty-one countries,[8] and Taiwan. Export approvals for uranium ore concentrates under the Regulations are managed in the framework of this network of agreements. Australia reports to the IAEA on exports of uranium ore concentrates on a monthly basis, under paragraph 34(a) of INFCIRC/153 for exports to non-nuclear-weapon states, and under the IAEA's Voluntary Reporting Scheme for exports to nuclear-weapon states.

On the other hand, exports of other ores and concentrates with trace, but extractable, concentrations of uranium for non-nuclear purposes are managed differently. Because these are exported for non-nuclear purposes, and because the decision-making authorities do prudent checks to satisfy themselves that this is the case, a bilateral nuclear cooperation agreement is not required and the exports are not reported to the IAEA under paragraph 34(a). For each export application, the decision by the authorized person is informed by a safeguards risk assessment performed by the Australian Safeguards and Non-Proliferation Office (ASNO), in consultation with other departments and agencies as necessary. The safeguards risk assessments are based on four factors: quantity of nuclear material; extractability of nuclear material; purpose of the export; and the nature of safeguards that would apply should uranium be extracted. Similar to the management processes for exports of dual-use goods under the Nuclear Suppliers Group (NSG) guidelines, exports of uranium-bearing ores and concentrates require official end-user assurances.

Conclusion

Effective regulatory controls on the production and export of uranium are very much in the national interests of governments and in the commercial interests of industry. As outlined in this paper, in most circumstances the level of IAEA oversight of uranium production and export is, by design, relatively limited. This is a result of the prevailing interpretation that the starting point of full safeguards, as defined in paragraph 34(c) of INFCIRC/153, commences at some point during the next stage of the fuel cycle, conversion of uranium ore concentrates to gaseous uranium hexa-fluoride.

Definitions of where full IAEA safeguards commence should not, however, be the yardstick against which the level of state regulation is set. For one thing the requirement under paragraph 7 of Comprehensive Safeguards Agreements for the state to establish a system of accountancy and control applies to all nuclear material subject to the Agreement, not just to the more highly processed material under full IAEA safeguards. Maintaining such a system enables the state to be sure when export reporting under paragraph 34(a) does and does not need to apply. This in turn helps maintain international confidence that the exporter is not contributing (inadvertently or otherwise) to any military nuclear programs. Paragraph 34(a) only requires reporting on exports to non-nuclear-weapon states, but in the same spirit of maintaining international confidence, it is important that exporters also report on exports to nuclear-weapon states under the IAEA's Voluntary Reporting Scheme.

It is widely appreciated that controls are required on exports of uranium for nuclear purposes, and most uranium producers do have such controls. However, it is not so widely appreciated that there can be risks associated with the export of ores and concentrates (such as mineral sands, tantalum concentrates, monazite and phosphates) with trace, but extractable, concentrations of uranium or thorium. Under paragraph 34(a) of INFCIRC/153 exports of these commodities must also be reported to the IAEA unless exported for specifically non-nuclear purposes. To ensure that such exports are in fact intended for non-nuclear purposes (as is usually the case), prudent measures should be in place by governments to assess the risks, and where necessary, control exports. Importantly, this is not just a matter of technical compliance with INFCIRC/153. With mostly robust controls on the exports of uranium ore concentrates, proliferators may instead seek to acquire uranium through unconventional means such as the commodities listed above.

Reference

1. Vestergaard, C. 2015. Moving the Starting Point of Nuclear Safeguards. *Danish Institute for International Studies (DIIS)*. www.diis.dk/en/node/4784.
2. East, M., C. Everton, and S. Bayer. 2013. Strengthening Safeguards Verification at Uranium Mines. Proceedings of the *54th INMM Annual Meeting.*
3. OECD Nuclear Energy Agency and International Atomic Energy Agency. 2014. Uranium 2014: Resources, Production and Demand (NEA No. 7209). www.oecd-nea.org/ndd/uranium/.
4. Australian Safeguards and Non-Proliferation Office. 2012. Facing the Proliferation Challenges of Unconventional Sources of Uranium. *Annual Report 2011-2012*. dfat.gov.au/international-relations/security/asno/Pages/annual-reports.aspx.

Footnotes

1. Note that this distinction has been re-examined by the IAEA recently in an internal IAEA guide known as Policy Paper 21, which considers how safeguards should apply to the production of high purity uranium ore concentrates. This, however, will not be examined in this paper.
2. Paragraph 34(a) does not apply to exports to nuclear-weapon states but a Voluntary Reporting Scheme introduced in the early 1990s encourages states to make these reports.
3. *Model Protocol Additional to the Agreement(s) between State(s) and the International Atomic Energy Agency for the Application of Safeguards* (IAEA document INFCIRC/540(corrected))
4. Information on the negotiating history of INFCIRC/153 can be found in: *Review of the Negotiating History of the IAEA Safeguards Document INFCIRC/153,* prepared by the Arms Control and Disarmament Agency, for the International Energy Associates Limited, 30 July 1984, (http://cgs.pnnl.gov/fois/documents.stm); which is a publicly available extensive summary of the IAEA's records in the series of GOV/COM.22 documents.
5. The IAEA Statute defines source material as: "uranium containing the mixture of isotopes occurring in nature; uranium depleted in the isotope 235; thorium; any of the foregoing in the form of metal, alloy, chemical compound, or concentrate."
6. Finnish proposal for INFCIRC/153 paragraph 34(a): "When any material containing uranium or thorium is exported for nuclear purposes directly or indirectly to a non-nuclear-weapon State, the State shall inform the Agency of its quantity, composition and destination." (GOV/COM.22/137)
7. The safeguards obligations described above make little differentiation between uranium and thorium. However, given there is essentially no thorium production and export industry for nuclear purposes to speak of, this paper focuses on uranium.
8. One agreement covers all twenty-eight Euratom countries.

Craig Everton is Director of the IAEA Safeguards Section in the Australian Safeguards and Nonproliferation Office (ASNO), with responsibility for administering Australia's national nuclear safeguards system, providing policy advice on international non-proliferation and safeguards issues, and managing Australia's international engagement on safeguards with the IAEA and other partners, such as through the Asia-Pacific Safeguards Network (APSN). In eleven years in ASNO, he has worked on managing Australia's compliance with IAEA safeguards requirements; specialist safeguards advice in the negotiations of several of Australia's bilateral nuclear cooperation agreements and associated administrative arrangements; negotiating safeguards resolutions at IAEA General Conferences; and, advising the government on international and domestic non-proliferation/safeguards matters. From 2010-11 he was a member of an IAEA Director General's Standing Advisory Group on Safeguards Implementation (SAGSI). Everton has a research master's of science in applied nuclear measurement techniques and a PhD in experimental particle physics, both from the University of Melbourne.

Acquisition Path Analysis Quantified – Shaping the Success of the IAEA's State-level Concept

Clemens Listner, Irmgard Niemeyer, Morton J. Canty
Forschungszentrum Jülich, Germany

Chantell L. Murphy
Los Alamos National Laboratory, Los Alamos, New Mexico USA

Gotthard Stein
Consultant, Bonn, Germany

Arnold Rezniczek
UBA GmbH, Herzogenrath, Germany

Abstract

The IAEA's Department of Safeguards has embarked on an evolutionary process to more fully develop and apply the state-level concept (SLC) for safeguards implementation. In an attempt to direct safeguards to areas of significant proliferation concerns within a state, this concept makes use of all safeguards-relevant information available in order to focus and prioritize its safeguards activities for a state.

A key component is the development of a customized safeguards approach for an individual state. Developing these state-level approaches consists of analyzing acquisition paths, establishing and prioritizing technical objectives, and identifying applicable safeguards measures. The paper presents a methodology to accomplish this process based on a three-step-approach: network modeling, network analysis, and strategic assessment.

The network modeling step assesses and models the state's nuclear capabilities as well as other state-specific factors concerning relevant proliferation scenarios. The network analysis step gives a ranking of all plausible acquisition paths including a visualization of the paths. Finally, the strategic assessment step evaluates the state's proliferation and compliance options as well as the IAEA's set of technical objectives and subsequent safeguards measures. In this paper, a hypothetical state model was developed in order to test the methodology's performance. Therefore, an Excel spreadsheet with all necessary state-level factors was created. Afterwards, a Python software module based on graph theoretical algorithms was applied to produce a comprehensive list of ranked acquisition paths including their visualization. The following step of the strategic evaluation is mainly based on the concept of the Nash equilibrium resulting in a stable combination of the state's and the IAEA's strategies. This formal and automatic procedure offers the advantage of gaining results in a comprehensive and non-discriminative manner.

Besides presenting and discussing the methodology in detail, results from an example case study will also show how this process could be carried out in practice. Furthermore, the problem of how to determine the model parameter "detection probability" will be discussed. The paper ends with conclusions and an outlook on planned future work in this area.

Introduction

Since the first ideas for supervising nuclear material, the verification system has evolved constantly. After gaining first experiences with item-specific safeguards according to the commitments in INFCIRC/66, the system of international safeguards was established by the signature and ratification of the Non-proliferation Treaty (NPT) in 1970. The treaty implementation has mainly been governed by comprehensive safeguards agreements (CSA) and later the additional protocol (AP) with Integrated Safeguards.

In order to verify the state's compliance to these provisions, the IAEA has been carrying out a mechanistic, checklist approach to safeguards with limited success. This method has been superseded over the past years by a holistic approach called the state-level concept (SLC). The SLC's main idea is to move away from material-centric approaches to a system analysis view of nuclear proliferation that clearly identifies the actors, their possibilities, and their risks. Due to its general and comprehensive nature, the SLC has great potential to replace voluntary offer agreements (VOA) in nuclear weapon states (NWS) and to be used in other fields of treaty verification.

Underneath the new paradigmatic view to nuclear verification, the state-level concept essentially consists of three processes that help to develop state-level safeguards approaches (SLA):[1]

- Identification of plausible acquisition paths.
- Specification and prioritization of state-specific technical objectives (TO).
- Identification of safeguards measures to address the technical objectives.

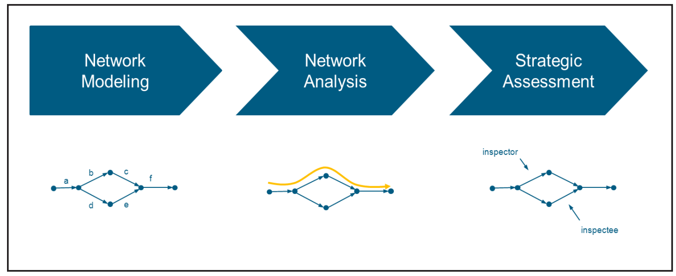
This paper concentrates on the first step of this process which is also known as acquisition path analysis (APA). APA is defined as the analysis of all plausible sequences of activities which a state could consider to acquire weapons usable material.[2] The purpose of the APA is to determine whether a proposed set of safeguards measures is sufficient. Therefore, some overlap to the second step, the definition of technical objectives, is obvious.

The approach to acquisition path analysis used in this paper has advanced over the past years.[3,4,5,6,7] Motivated from the fact that the SLC tries to come up with adaptive safeguards approaches, the main idea of this approach to APA is to account for differentiation without discrimination. In order to accomplish this, the available safeguards-relevant information is processed in an objective, transparent, reproducible, standardized, and well-documented way in contrast to classical reasoning-with-words or black-box-approaches.

Besides the methodology and its progress, the new verification paradigm has to be compatible with the existing approach to nuclear material accounting, a major element of traditional safeguards. Therefore, it will be shown how performance targets can be derived from a risk assessment of the state's as well as the inspectorate's strategic options.

Moreover, the determination of the model parameters has turned out to be a non-trivial task.[5] Especially, when it comes to detection probabilities that can be reasonably claimed within a technical objective, the user needs to consider the detection of proliferation activities in declared facilities as well as in potential undeclared installations. This paper proposes four concepts for how to overcome this issue.

Figure 1. Three step approach to acquisition path analysis



In the following, the methodology and its recent enhancements will be presented. Then, a discussion on the relationship between game theory and performance targets will be carried out. Afterward, a case study focusing on the strategic assessment part of the method will be shown. Next, some considerations will be given to the determination of model parameters, especially the quantification of detection probabilities. Finally, conclusions of the paper and an outlook on future work will be presented.

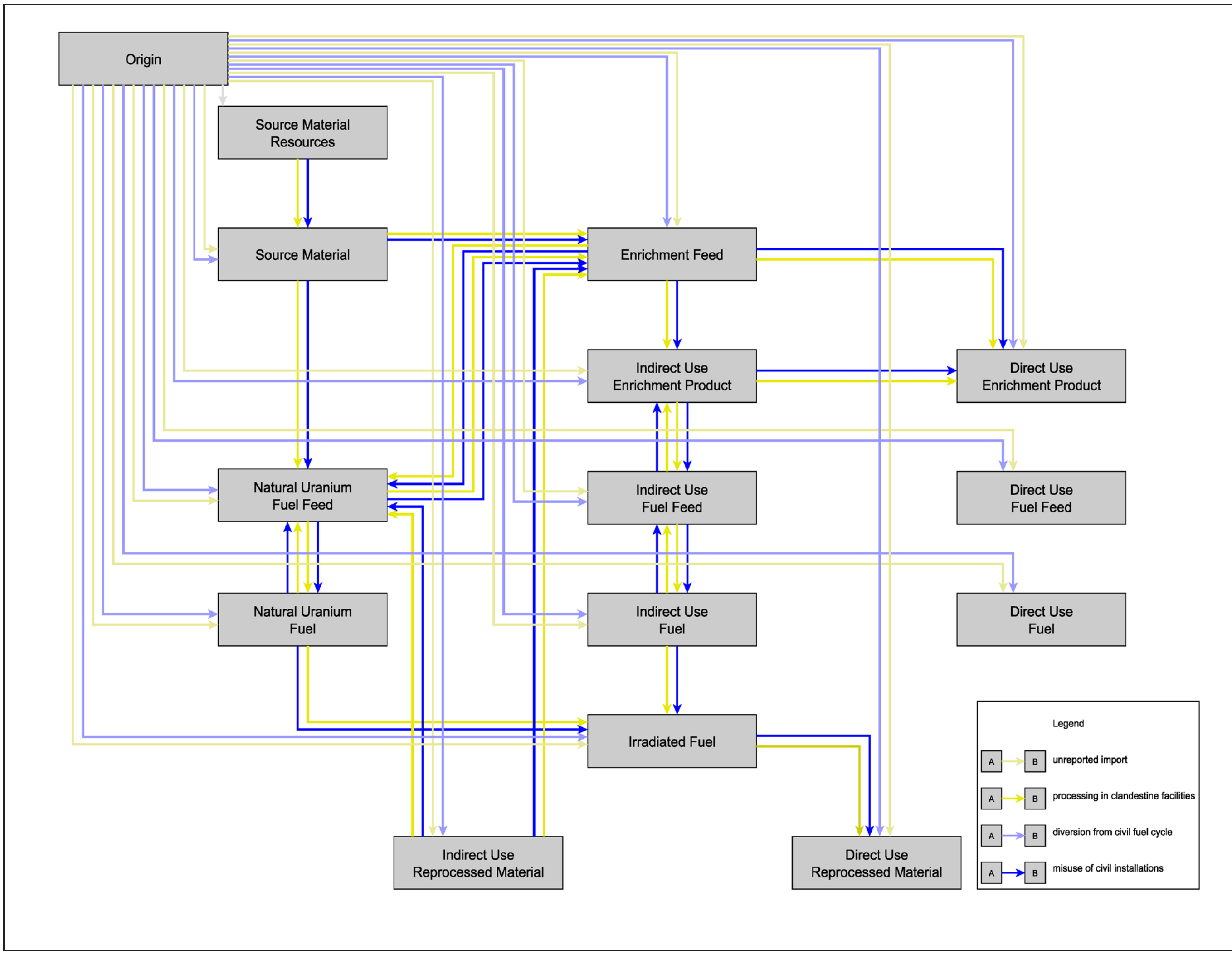
Materials and Methods

The given approach to acquisition path analysis consists of three general steps. First, the potential acquisition network is modeled based on the IAEA's physical model and experts' evaluations. Second, using this model all plausible acquisition paths are extracted automatically. Third, the state's and the inspectorate's options are assessed strategically. The workflow is depicted in Figure 1. In the following, a description of the three stages will be given. A more in-depth discussion can be found in Listner et al.[8]

During the first step of the process, also known as network modeling, a state-specific acquisition model is set up. Mathematically, such a network can be seen as a directed graph with material forms represented by nodes and processes represented by edges. The IAEA's physical model[9] serves as a starting point, where all proliferation-relevant materials and processes are formally described in a general acquisition model for nuclear weapons-usable material. Based on the IAEA's physical model, a mathematical model has been derived that encodes all the potential materials and activities in a single directed graph (see Figure 2).

There are four categories of processes in this model: diversion from existing facilities (div), undeclared import (imp), misuse of existing facilities (mis), processing in clandestine facilities (cland). When assessing a state's options for acquiring nuclear weapons usable material, specific processes of these

Figure 2. Generic physical model



four types are included in or excluded from the model. For example, if a state does not have an enrichment facility on its ground, all edges of type misuse in connection with enrichment will be removed from the model. On the other hand, there will be always the option for enriching in clandestine facilities and hence these processes will remain in every state's case.

Besides the mere presence of edges in the model, these edges will be assessed in terms of attractiveness for the particular state. Three dimensions of attractiveness are used which originate in the GIF methodology:[10] Technical Difficulty (TD), Proliferation Time (PT), and Proliferation Cost (PC). For each process, the three dimensions are graded based on expert judgment. The grades range from 0 meaning a very attractive option to 3 being very unattractive. Using the arithmetic mean for each edge *e*, a single edge weight is calculated from these figures.

After having specified the edge weights, it is necessary to model the inspectorate's side, i.e., the possible technical objectives *t* with their respective non-detection probability $\beta_e^{(t)}$ on a specific edge *e*. Also the inspectorate costs c_t generated by technical objective *t* have to be quantified. Although no specific safeguards measures have been determined at this point, an expert can estimate the costs for attaining a given detection probability based on experience and knowledge about the state's capabilities, fuel cycle as well as existing safeguards approaches. While these figures can be specified for the edges related to the declared fuel cycle, i.e., misuse and diversion, deriving this information for the undeclared processes, i.e., undeclared import and clandestine processing, is yet an unsolved task. However, the given approach assumes that such quantification can in principle be done for all types of processes, no matter whether they take place in declared facilities or elsewhere in the state.

As a result of the first step, a directed multi-graph is produced that represents the state's options for acquiring weapons usable material including their attractiveness in terms of time, cost and technical difficulty. Furthermore, also the inspectorate's options to control the activities are given, including the costs and non-detection probabilities in specific areas of the state's acquisition network.

Table 1. Game theoretic payoffs

	No Alarm	Alarm
Compliant Behavior	(0,0)	*(-f,-e)*
Non-compliant Behavior Along Path	*(di,-c)*	*(-b,-a)*

This directed multi-graph is now analyzed in terms of all technically plausible acquisition paths. In order to accomplish this, a fully automated software extracts all paths from node 'Origin' to any node representing weapons usable material by applying the Depth-First-Search (DFS) algorithm.[11] For each path ρ_i, the overall attractiveness is calculated by the sum of the weights of the constituting edges $E(\rho_i)$, i.e.,

$$l_i = \sum_{e \in E(p_i)} w_e. \quad (1)$$

The list of paths is then reordered by attractiveness and all paths are visualized. It has to be emphasized that not only the shortest path but all technically plausible paths are considered. Therefore, this approach is comprehensive and avoids ignoring technically less attractive paths which could be strategically interesting.

Using the results of the first and second step, especially the list of paths with their respective attractiveness as well as the non-detection probabilities of technical objectives, the third step assesses the strategies of both parties, i.e., the state and the inspectorate. On the one hand, all acquisition paths and the option of compliant behavior are considered to be the state's strategy set. On the other hand, the strategies of the IAEA are all combinations of technical objectives (TOC) that have been defined in the first part of the process. The overall non-detection probability of TOC_j for a given path ρ_i can be calculated using the product rule for probabilities by

$$\beta_{ij} = \prod_{e \in E(p_i), t \in TOC_j} \beta_e^{(t)}. \quad (2)$$

For each strategy combination a pair of payoff values for state and Inspectorate (H_1, H_2) can be defined (see Table 1). For the IAEA, the strategic outcomes in increasing order of preference are undetected non-compliance (–*c*), detected non-compliance (–*a*), false alarm (–*e*) and compliance without alarm (0). These parameters can be selected freely as long as the ordering is kept.

Regarding the state, the strategic outcomes ordered increasingly by preference are detected non-compliance (–*b*), false alarm (-*f*), compliance without alarm (0) and successful acquisition along path p_i (d_i). The path length *li* calculated in step two is used to obtain the payoff values for successful acquisition by

$$d_i = \frac{l_1}{l_i}. \quad (3)$$

The decision whether an alarm is raised by the inspectorate depends on the non-detection probabilities. Hence, for each strategy combination an expected outcome for both players can be calculated. In case the state decides to follow an acquisition path and the IAEA has in place, this payoff for the state is given by the expected benefit from a successful acquisition plus the risk of getting caught red-handed, i.e.

$$H_1^{(i)} = d_i \beta_{ij} - b(1 - \beta_{ij}). \quad (4)$$

For the IAEA, the expected payoff can be derived from the sum of the risks of detected and undetected non-compliance, i.e.,

$$H_2^{(i)} = -c\beta_{ij} - a(1 - \beta_{ij}). \quad (5)$$

In case the state behaves in compliance with its given commitments, the outcome for both sides is only determined by the false alarm risk with false alarm probability, i.e.,

$$H_1^{(compliant)} = -f\alpha_j \quad (6)$$

for the state and

$$H_2^{(compliant)} = -e\alpha_j \quad (7)$$

for the IAEA.

Based on these considerations, a stable strategy combination (H_1*, H_2*) known as the Nash equilibrium can be calculated using the Lemke-Howson-algorithm.[12] The Nash equilibrium is characterized by the fact that it is impossible for either of the two actors to deviate unilaterally from the equilibrium strategy and increase its expected payoff. Hence, it seems rational for both players not to deviate and pursue the equilibrium strategy. This very limited definition of rationality only means that the actors care for the risks and benefits they are facing.

Using the equilibrium payoff value for the IAEA and scaling the IAEA's payoff parameters to c=1, it is possible to define effectiveness as

$$E = 100\% + H_2^*. \qquad (8)$$

In case of 0 percent effectiveness, the equilibrium ends in non-compliance with no possibility of detection. For effectiveness, compliance with no false alarm is achieved almost surely. As the ultimate goal of acquisition path analysis is the selection of a TOC inducing compliant behavior (expressed by the term sufficient in the APA definition), this paper proposes to use a TOC leading to a high effectiveness value in the Nash equilibrium.

Moreover, in cases where compliant behavior can be induced in the Nash equilibrium, it is also possible and reasonable to gain an increase in efficiency. By iterating over a cost threshold and calculating the Nash equilibrium for this range of values, a strategy with a given level of effectiveness at minimum costs can be selected.

Strategic Assessment Using Performance Targets and Game Theory

In the previous section, it has been shown what a game theoretic, highly quantitative approach to technical objectives determination could look like. Alternatively, a more qualitative approach based on the idea of performance targets[13] can be used, which gives more flexibility to the analyst. This section will show that the philosophy behind these two different approaches to APA can be considered to be equivalent.

A performance target on the path level can be defined as the minimum detection probability that is needed in order to deter a state from pursuing this path. This means that if performance targets are properly defined for a given set of acquisition paths, these paths can be considered to be adequately covered by safeguards measures. Hence, the state is likely to act in compliance with its given commitments.

More formally, one can say that for given acquisition path ρ_i and technical objectives combination TOC_j, path coverage is achieved if the risk for the state to get caught along the path is higher than the benefit of a successful acquisition[c], i.e.,

$$d_i \beta_{ij} - b(1 - \beta_{ij}) \leq 0. \qquad (9)$$

In the past, the IAEA has considered it to be sufficient to obtain a detection probability of 90 percent in nuclear facilities with high potential to be used in nuclear weapons programs. Transferring this to the idea of acquisition path analysis, for the most attractive path a performance target of 90 percent should be reached. As it has been shown in Avenhaus and Canty,[14] this directly influences the choice of the payoff values in Equation 9, i.e.,

$$0 \geq d_1 \cdot 0.1 - b \cdot 0.9,$$
$$9 \geq {d_1}/{b}.$$

Because the payoff values are ranging from 0 to 1 (see Equation 3) with d_1=1, the state's payoff for a successful acquisition is b=1/9.

Using these parameter values derived for the most attractive path, one can reinsert them into Equation 9 which leads to

$$\beta_{ij} \leq \frac{b}{d_i + b} = \frac{1}{9\frac{l_1}{l_i} + 1}. \qquad (10)$$

This gives a rationale to define the path performance targets for the detection probability based on its attractiveness as

$$PT_i = DP_i^{(\min)} = 1 - \beta_{ij}^{(max)} = \frac{l_1}{l_1 + l_i b}. \qquad (11)$$

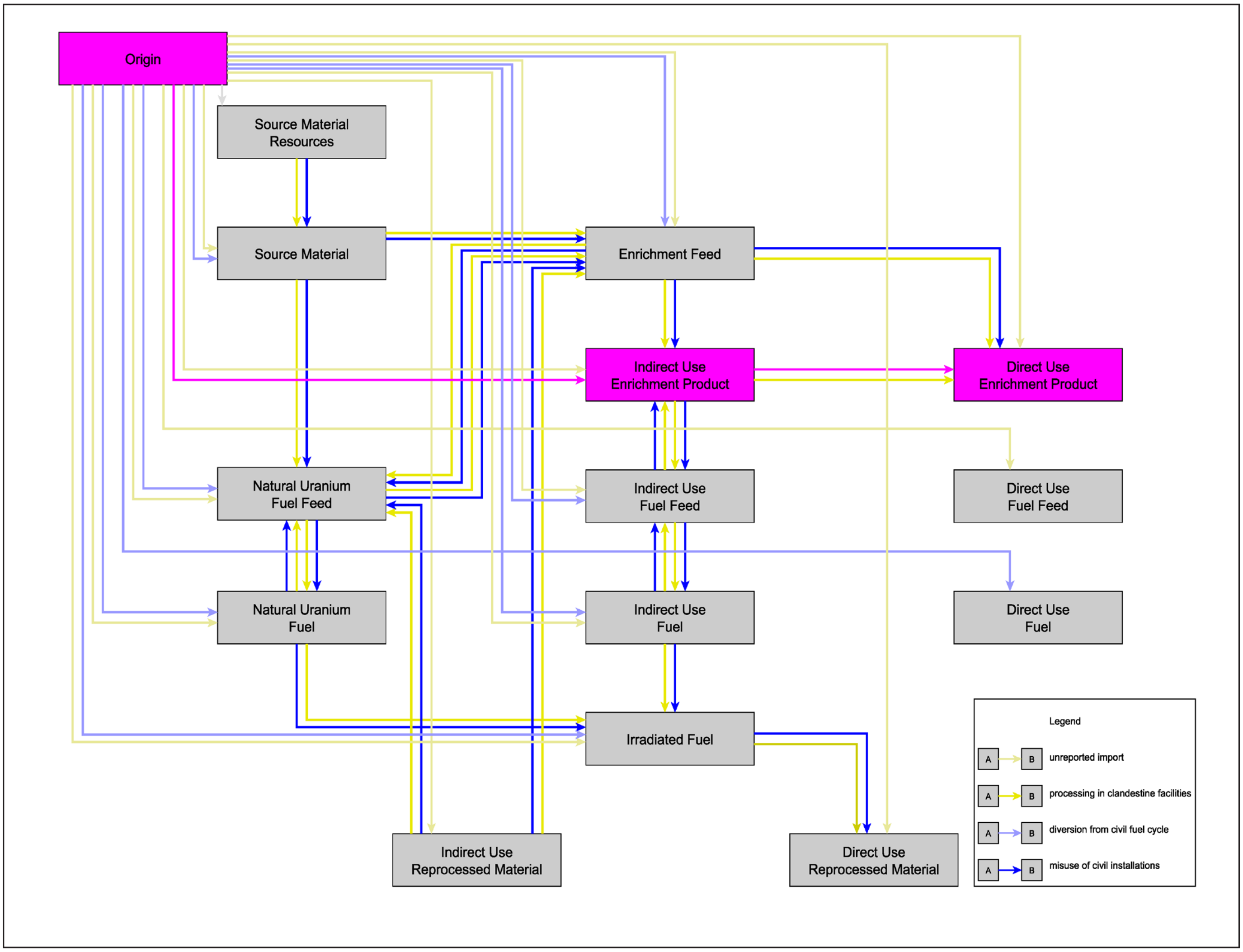
This calculation of performance targets can be used within the methodology of Budlong Sylvester et al.[15] in order to specify the appropriate technical objectives. If all performance targets are fulfilled, it is guaranteed under the assumptions of the model that the state will chose to behave in compliance with its commitments.

While the methodology in Budlong Sylvester et al.[15] leaves the decision up to the analyst which technical objectives to choose, the methodology presented previously uses an optimization technique to determine them. From the standpoint of the underlying philosophy however, both methods are equivalent.

Example Case Study

In order to prove the feasibility of the concept described in the previous sections, a case study was carried out. Therefore, a

Figure 3. Visualization of the fifth most attractive path. The path highlighted in magenta represents the diversion of low enriched UF_6 from the declared enrichment facility and misusing the enrichment facility in order to produce direct use material.



hypothetical state with a complex civil nuclear fuel cycle and comprehensive capabilities was modeled. Attractiveness values as well as costs and detection probabilities for technical objectives were determined using expert judgement. Following that, a set of 2060 plausible acquisition paths was calculated and sorted according to their attractiveness. Furthermore, a visualization was generated (see Figure 3).

In order to allow for a manual determination of technical objectives according to Section 3, twenty-one paths out of the 2060 paths were selected for further analysis. At this stage of the process, performance targets were calculated for the selected paths using Equation 11. The selected paths with their associated attractiveness, payoff values and performance targets are displayed in Table 2.

Finally, the strategic assessment, restricted on the twenty-one paths, was carried out using an approach which iterated over the cost limit as it was described previously. As previous studies have shown, the results are highly dependent on the detection probability for clandestine activities, $DP_{c/and}$, the algorithm ran for different values of this parameter. The results are displayed in Figure 4. The alternative approach to technical objectives selection as described in Budlong Sylvester et al.[15] was beyond the scope of this paper.

Specifying the Model's Parameters

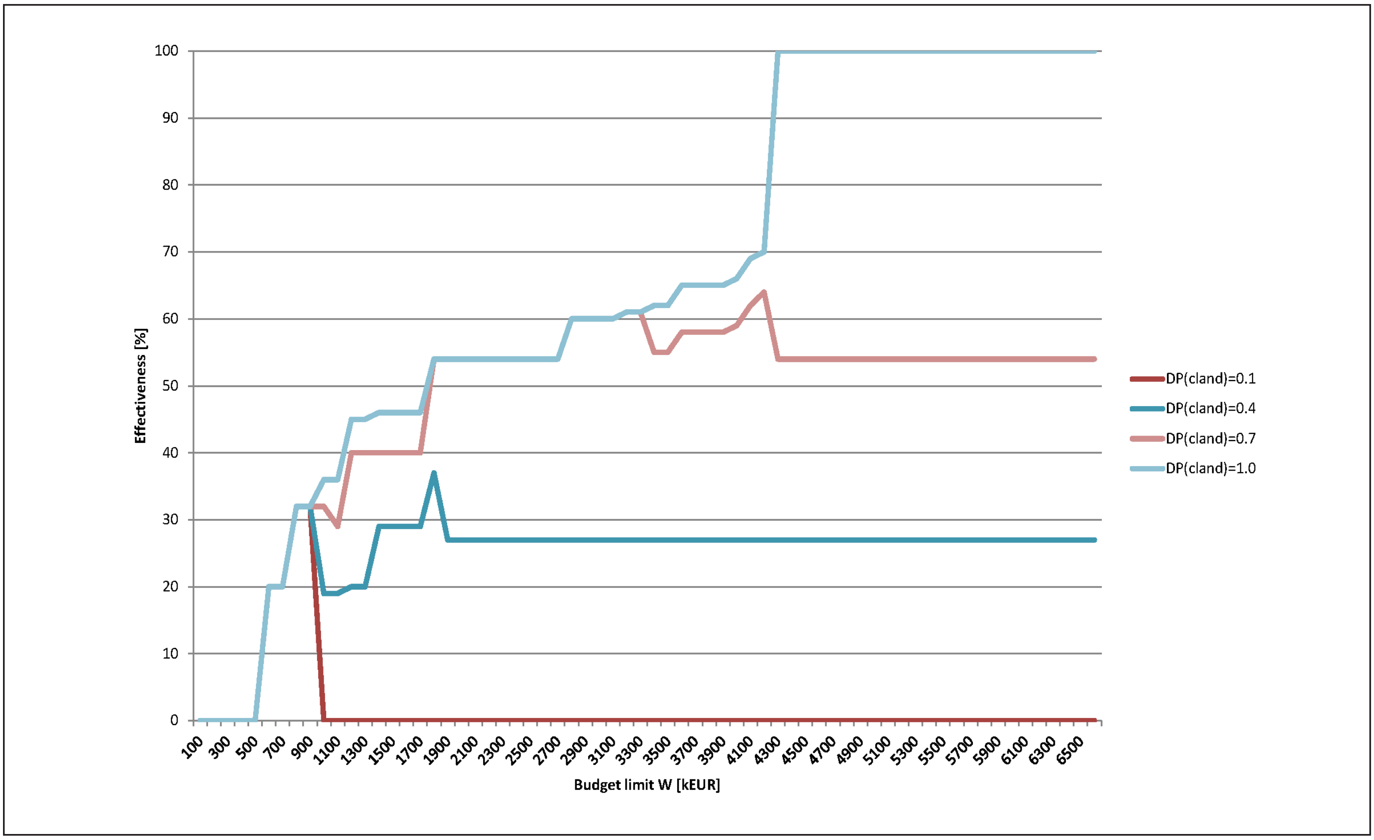
The previous sections have shown how the APA model can be used to determine an optimal set of technical objectives. As input on behalf of the state, the model requires an assess-

Table 2. List of paths selected for strategic assessment along with path index, description of the path, overall path attractiveness, performance target and payoff value.

i	Description	I_i	PT_i	d_i
1	Origin -imp- Direct Use Enrichment Product	2.33	90%	1.0
5	Origin -div- Indirect Use Enrichment Product -mis- Direct Use Enrichment Product	3.0	88%	0.78
8	Origin -div- Irradiated Fuel -mis- Direct Use Reprocessed Material	3.67	85%	0.64
14	Origin -div- Enrichment Feed -cla- Direct Use Enrichment Product	4.33	83%	0.54
22	Origin -div- Indirect Use Fuel -mis- Irradiated Fuel -mis- Direct Use Reprocessed Material	4.33	83%	0.54
27	Origin -imp- Indirect Use Reprocessed Material -mis- Enrichment Feed -mis- Direct Use Enrichment Product	4.67	82%	0.5
39	Origin -div- Source Material -mis- Enrichment Feed -cla- Direct Use Enrichment Product	5.0	81%	0.47
40	Origin -imp- Source Material -cla- Enrichment Feed -mis- Direct Use Enrichment Product	5.0	81%	0.47
44	Origin -imp- Natural Uranium Fuel -mis- Irradiated Fuel -cla- Direct Use Reprocessed Material	5.0	81%	0.47
58	Origin -div- Indirect Use Fuel -cla- Irradiated Fuel -cla- Direct Use Reprocessed Material	5.33	80%	0.44
65	Origin -imp- Natural Uranium Fuel -mis- Natural Uranium Fuel Feed -mis- Enrichment Feed -mis- Direct Use Enrichment Product	5.33	80%	0.44
67	Origin -imp- Indirect Use Fuel -mis- Indirect Use Fuel Feed -mis- Indirect Use Enrichment Product -mis- Direct Use Enrichment Product	5.33	80%	0.44
68	Origin -div- Source Material Resources -cla- Source Material -cla- Enrichment Feed -mis- Direct Use Enrichment Product	5.33	80%	0.44
73	Origin -div- Enrichment Feed -mis- Indirect Use Enrichment Product -cla- Direct Use Enrichment Product	5.67	79%	0.41
88	Origin -imp- Source Material -mis- Enrichment Feed -mis- Indirect Use Enrichment Product -mis- Direct Use Enrichment Product	5.67	79%	0.41
95	Origin -imp- Natural Uranium Fuel -mis- Natural Uranium Fuel Feed -cla- Enrichment Feed -mis- Direct Use Enrichment Product	5.67	79%	0.41
125	Origin -div- Source Material Resources -cla- Source Material -cla- Enrichment Feed -cla- Direct Use Enrichment Product	6.0	78%	0.39
164	Origin -div- Source Material Resources -mis- Source Material -mis- Natural Uranium Fuel Feed -mis- Natural Uranium Fuel -mis- Irradiated Fuel -mis- Direct Use Reprocessed Material	6.33	77%	0.37
262	Origin -imp- Indirect Use Reprocessed Material -mis- Natural Uranium Fuel Feed -mis- Natural Uranium Fuel -mis- Irradiated Fuel -cla- Direct Use Reprocessed Material	7.33	74%	0.32
538	Origin -div- Source Material Resources -mis- Source Material -mis- Enrichment Feed -mis- Indirect Use Enrichment Product -mis- Indirect Use Fuel Feed -mis- Indirect Use Fuel -mis- Irradiated Fuel -mis- Direct Use Reprocessed Material	9.0	70%	0.26
1509	Origin -div- Source Material Resources -cla- Source Material -cla- Enrichment Feed -cla- Indirect Use Enrichment Product -mis- Indirect Use Fuel Feed -cla- Indirect Use Fuel -mis- Irradiated Fuel -mis- Direct Use Reprocessed Material	12.0	64%	0.19

ment of each process' attractiveness and the resulting payoff values for each path d_i. On behalf of the inspectorate, for each technical objective a cost estimate is needed as well as an estimate of the non-detection probability for each process given that a technical objective is in place. It turns out that the attractiveness values, the cost estimates and the non-detection probabilities in terms of declared facilities can be obtained relatively easily because there are models available for the estimation of these parameters. However, until now there are no models available for the estimation of non-detection probabilities for processes in covert facilities as well as undeclared import.

Figure 4. Effectiveness chart retrieved from game theoretic analysis



In the past, the estimation of such non-detection probabilities has been considered to be an impossible task. The reasons for the reluctance to quantify these parameters can be found in the lack of system boundaries of clandestine nuclear facilities as they can be located anywhere in a state. The same applies to the case of undeclared import, where the location of possible indicators could even be found worldwide. Moreover, it is not even clear which indicators could give the relevant hint to a clandestine facility.

All these problems seem to be good reasons to tackle the detection of clandestine facilities and undeclared import only in a qualitative way. However, this would lead to the problem of how to justify the budget expenditures on the detection of clandestine facilities against conventional safeguards measures whose effectiveness can be quantified very elegantly. A model calculating quantitative estimates for the non-detection probabilities can overcome this issue. Also, this problem is similar to effectiveness quantification in the intelligence realm and there has been research on how to address this (see Reference 16).

Table 3. Verification error matrix

	No Alarm	Alarm
Compliance	$1-\alpha$	α
Non-Compliance	β	$1-\beta$

In the past it has been shown that hypothesis testing is a powerful tool that can be applied in the context of treaty verification to estimate the errors (see Reference 17). It assumes that a state can behave either compliantly or not. In contrast, the inspectorate has the possibility to raise an alarm or not. Thus, the error model results in four event combinations which are displayed in Table 3. The main diagonal entries of this matrix indicate a properly working verification system which raises an alarm in case of non-compliance or does not in case of compliance. The off-diagonal elements however reflect errors in the verification system. An error of the first kind, also known as a false alarm, will occur, if the state behaves compliantly but the inspectorate raises an alarm despite that fact. This error's probability is denoted by. The error of the second kind is also known as non-detection of incompliance. This error will occur, if the state proliferates but the inspectorate is not able to detect this behavior and thus will not raise an alarm. This error's probability is denoted by β.

Based on this error model, the existing literature and developing new ideas, four possibilities will be presented how to estimate the non-detection probabilities in case of undeclared facilities or import. These suggestions should be seen as a starting point for further discussion and research.

Possibility A: The Analogy Approach

The first and by far the simplest possibility starts by looking into declared facilities. There, the safeguards system can obtain a non-detection probability of $\beta_{declared}$ = 10 percent if all measures, like e.g., PIVs and IIVs, are in place. By analogy, the same non-detection probability of $\beta_{undeclared}$ = 10 percent is assumed for undeclared facilities in case all measures, like e.g., open source information analysis taskings, are applied here as well. If only parts of the measures are applied, a linear scaling procedure increases the non-detection probability.

For example, in case only half of the measures are applied, the detection probability reduces from $1-\beta_{undeclared}$ = 90% to $1-\beta_{undeclared}$ = 45 percent.

This approach gives a model which is very simple and easy to understand. However, a validation of the stated non-detection probabilities is merely impossible.

Possibility B: The Bayesian Approach

The second approach uses Bayes' theorem to model the information analysis process and then estimates the detection probability from a simulation step. In this context, the event A_j means that the proliferation activity j, e.g. the use of a clandestine reprocessing facility, is carried out by the state. $B=\{B_1,\ldots,B_n\}$ represent the set of available information pieces. Based on these probabilistic events, the Bayes formula retrieves the probability of a proliferation activity A_j given a set of available information B as

$$P(A_j|B) = \frac{P(B|A_j)P(A_j)}{P(B|A_j)P(A_j)+P(B|\bar{A}_j)P(\bar{A}_j)} \quad (12)$$

In this formula, the probabilities $P(B|\bar{A}_j)$ can be derived from the physical model which lists indicators, i.e., pieces of information, with their probability of occurrence in case a specific proliferation activity is carried out. The probabilities given the complementary events $P(B|\bar{A}_j)$ would have to be estimated by experts in a similar way. However, the question how to obtain the prior probabilities $P(A_j)$ and $P(\bar{A}_j)$ remains open.

Once the Bayes formula is applied to derive the probability $P(A_j|B)$, the information analysis process would raise an alarm, if this probability exceeds a given threshold T. In order to derive the non-detection probabilities β, one checks the correctness of the information analysis process for any combination of B, A_j and $\bar{A}_j$ weighted by the probability of each event combination. The error of the first second kind then gives the non-detection probability β. Again, estimating the prior probability of each event combination remains an unsolved problem.

As a conclusion, the Bayesian approach helps to structure the problem of quantifying detection probabilities in a qualitative environment. Moreover, the physical model already includes certain information which can serve as input. However, it is a non-trivial task to obtain the prior probability of a proliferation activity. In order to be non-discriminatory, the methodology would have to assume the same priors for each state although this hardly reflects reality.

Possibility C: The Frequentist Approach

As a third possibility, historical events in the field of non-proliferation can be used to retrieve estimates for the non-detection probability. Therefore, the error matrix is filled with the absolute number of events (see Table 4). Using these figures, the non-detection probability can be estimated using

$$\hat{\beta} = \frac{H_{undetected\ non-compliance}}{H_{undetected\ non-compliance}+H_{succesful\ detection}}. \quad (13)$$

Similarly, an estimate for the false alarm probability can be given by

$$\hat{\alpha} = \frac{H_{false\ alarm}}{H_{false\ alarm}+H_{compliance\ without\ alarm}}. \quad (14)$$

In practice, the number of events can be obtained from the safeguards implementation report or other sources of information. Also, one could think of aggregating the data using different criteria such as counting only events that took place in a single year that refer to a particular state or that cover a specific proliferation activity.

Table 4. Estimated verification error matrix

	No Alarm	Alarm
Compliance	$H_{compliance\ without\ alarm}$	$H_{false\ alarm}$
Non-Compliance	$H_{undetected\ non-compliance}$	$H_{succesful\ detection}$

The advantages of this approach result from the strong quantitative basis and the simplicity of only counting events is required. However, the disadvantage of relatively few data points for non-compliance are obvious. This could be a source of error.

Possibility D: The Process Approach

Finally, the fourth approach considers α and β to be "measurement errors" of the inspectorate's information analysis process. This information analysis process can be subdivided into five components according to the intelligence cycle (see Reference 18): plan, collect, process, analyze, disseminate.

For each sub-process ρ_j, this approach estimates the errors for a false alarm, α_j, and non-detection, β_j, based on the error sources within the respective sub-processes. Assuming independence of error probabilities among the sub-processes, the overall errors can then be calculated as

$$\alpha_{total} = 1 - \prod_{j=1}^{5}(1 - \alpha_j) \quad (15)$$

and

$$\beta_{total} = 1 - \prod_{j=1}^{5}(1 - \beta_j). \quad (16)$$

An advantage of this approach is the fact that it helps structuring the problem of estimating verification error probabilities despite the absence of complete error models. It also gives hints where to improve the information analysis process. However, the quantification of errors is still necessary on a lower level. This is not easy to accomplish for all sub-processes of the information analysis process.

Conclusions and Outlook

This paper shows how acquisition path analysis can be carried out using a comprehensive methodology which is yet compatible with the principles defined in Cooley.[1] Furthermore, two possibilities for determining technical objectives were proposed and evaluated. The first more quantitative approach delivers a set of technical objectives with optimal effectiveness under the assumptions of a game theoretic model. Besides the high degree of automation, this approach also allows for an inherent randomization of technical objectives. However, the analyst has to specify a set of parameters in this approach. Therefore a good understanding of the model is necessary, as the influence of the parameters on the model's outcome is very complex.

The alternative approach overcomes these drawbacks by a higher degree of interaction with the analyst. Moreover, it allows for re-prioritization of paths based on possible indications. On the other hand, this flexibility leads to less reproducibility of the results when transferring the task to a different analyst.

In summary, while the underlying philosophy is the same, both methodologies have their advantages and disadvantages. However, it also has been shown that the underlying philosophy is the same.

A major point of criticism of a formal approach to acquisition path analysis is the question of how to quantify the non-detection probabilities of proliferation activities outside declared facilities. As a starting point for discussion, this paper outlines four approaches how this quantification could be implemented.

In the future, further case studies need to be carried out. Also, the outcomes sensitivity on the selected parameters in both approaches will be investigated. Furthermore, the applicability of the presented ideas to other applications in the area of arms control and disarmament will be investigated. Finally, the methodology will be iteratively improved with the help of experts at the IAEA.

Acknowledgments

This paper was prepared as an account of work sponsored by the government of the Federal Republic of Germany within the Joint Program on the Technical Development and Further Improvement of IAEA Safeguards between the Federal Republic of Germany and the IAEA.

Clemens Listner is a research assistant at Forschungszentrum. He is charged with conducting research on non-proliferation and international safeguards as well as developing acquisition path analysis methodologies and software for the IAEA's state-level concept. He works in EU-funded project G-SEXTANT. Listner obtained his PhD in Geoinformatics, from TU Bergakademie Freiberg, Germany in 2014.

End Notes

A. In principle, the weaponization step itself could be modeled using a graph theoretic approach. However, due to the definition of acquisition path analysis given by the International Atomic Energy Agency (IAEA), this paper's approach ends at weapons usable material.

B. These dimensions only represent technical aspects of proliferation as if no inspectorate was present. The interplay of State and inspectorate will be considered separately in the third stage of the process.

C. For reasons of simplicity, false alarm risks are ignored in this paper. A similar argument can be made if false alarm risks are included in the model.

References

1. Cooley, J. N. 2011. Progress in Evolving the State-level Concept, *Seventh INMM/ESARDA Joint Workshop Future Directions for Nuclear Safeguards and Verification*.
2. International Atomic Energy Agency (IAEA). 2001. IAEA Safeguards Glossary. In: *International Nuclear Verification Series No. 3*.
3. Listner, C., et al. 2012 A Concept for Handling Acquisition Path Analysis in the Framework of IAEA's State-level Approach, *Proceedings of the 53rd INMM Annual Meeting*.
4. Listner, C., et al. 2013. Approaching Acquisition Path Analysis Formally—Experiences So Far, *Proceedings of the 54th INMM Annual Meeting*.
5. Listner, C., et al. 2013. Approaching acquisition path analysis formally - a comparison between AP and non-AP States, *Proceedings of the 35th ESARDA Annual Meeting*.
6. Listner, C., et al. 2014. Evolution of Safeguards - What Can Formal *Proceedings of the INMM 55th Annual Meeting*.
7. Listner, C., et al. 2014. Quantifying Detection Probabilities for Proliferation Activities in Undeclared Facilities, Symposium on International Safeguards: Linking Strategy, Implementation and People.
8. Listner, C., et al. 2013. *A Concept for Handling Acquisition Path Analysis in the Framework of IAEA's State-level Approach*. Tech. rep. JOPAG/04.13-PRG-400.
9. International Atomic Energy Agency (IAEA). 1999. The Physical Model. STR-314.
10. GEN IV International Forum. 2006. *Evaluation Methodology for Proliferation Resistance and Physical Protection of Generation IV Nuclear Energy Systems*.
11. Cormen, T. H., et al. 2001. *Introduction to Algorithms*. 2nd. Cambridge, MA, USA: MIT Press.
12. Canty, M. J. 2003. *Resolving Conflicts with Mathematica: Algorithms for Two-person Games*.
13. Murphy, C. L., et al. 2014. Evolution of Safeguards - An Information-driven Approach to Acquisition Path Analysis, *Proceedings of the 55th INMM Annual Meeting*.
14. Avenhaus, R., and M. J. Canty. 2006. Formal Models of Verification. In: *Verifying Treaty Compliance*. Ed. by R. Avenhaus, et al. Springer.
15. Budlong Sylvester, K. W., et al. 2014. The Use of Performance Targets in the State-Level Concept, *Proceedings of the 55th INMM Annual Meeting*.
16. Lehner, P., et al. 2010. *Measuring the Forecast Accuracy of Intelligence Products*. Tech. rep. MITRE.
17. Avenhaus, R., and M. J. Canty. *Compliance Quantified*. Cambridge University Press Cambridge, 1996.
18. *The Intelligence Cycle*. 2013. Retrieved from https://www.cia.gov/kids-page/6-12th-grade/who-we-are-what-we-do/the-intelligence-cycle.html.
Central Intelligence Agency. March 2013.

Nomenclature

AP	additional protocol
APA	acquisition path analysis
cland	processing in clandestine facilities
CSA	comprehensive safeguards agreements
DFS	Depth-First Search
div	diversion from existing facilities
imp	undeclared import
mis	misuse of existing facilities
NPT	Non-proliferation Treaty
NWS	nuclear weapon state
PC	Proliferation Cost
PT	Proliferation Time
SLA	State-level approach
SLC	State-level concept
TD	Technical Difficulty
TO	technical objectives
TOC	technical objectives combination
VOA	voluntary offer agreement

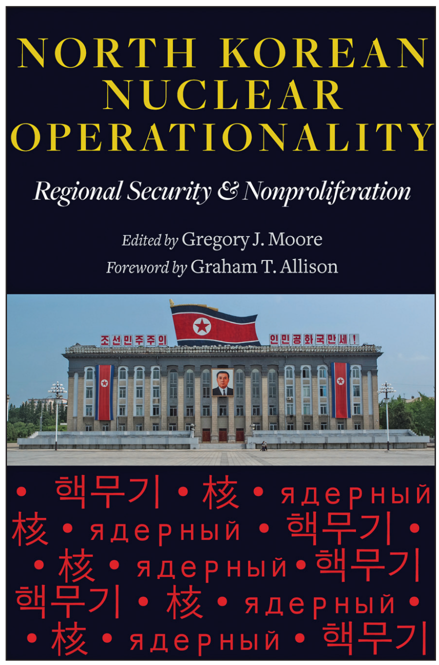
Book Review

By Mark L. Maiello, PhD
Book Review Editor

North Korean Nuclear Operationality

Gregory J. Moore, Editor
Hardcover, 302 pages
ISBN 978-1-4214-1094-4
Johns Hopkins University Press
Baltimore, MD, 2014

Richly detailed and logically laid out, Moore's book is an excellent analysis of North Korea's acquisition of nuclear arms and the consequences to its neighbors. A wide spectrum of issues concerning this threat to the Nuclear Nonproliferation Treaty (NPT) are examined including the long evolution of the crisis, the motivations behind the North Korean regimes seeking nuclear weapons, and the uniqueness of the predicament that has trapped North Korea in its competitive dilemma with South Korea and leaving the six nations dealing with the Democratic Peoples Republic of Korea (DPRK) more or less impotent to punish it or deal effectively with it. This effort utilizing the expertise of twelve specialists from Japan, Australia, China (the author is based in Zhejiang University), South Korea, Russia, and the United States, brings the reader a very broad perspective and in so doing elevates the examination well beyond the U.S. vs. DPRK ("us vs. them") argument. The language is very accessible, free for the most part of political science jargon, and not until the much appreciated last summary chapter, also free of political science analysis—a plus for nuclear scientists seeking to understand the nuts and bolts of the crisis.



This is a well-constructed read, taking the curious through the DPRK's current nuclear status (just shy of operationality until and if weapon miniaturization and missile capability reach a mutual accommodation). But does that matter? As stated later in the book, the damage to the NPT is done: the DPRK created nuclear weapons after disengaging from its treaty obligations. However, before addressing the affects the crisis is having on the nonproliferation regime, the reader is treated to a discourse on the U.S. failure to address the issue, and how it might rectify the lack of success by putting the DPRK on the defensive through the use of incentives it would find difficult to refuse and that would leave it vulnerable to severe international repercussions if after accepting them it continued its brinkmanship and antagonistic behavior. This discussion is followed by others written by the aforementioned regional experts who seek to explain how nuclear operationality by DPRK affects their nations. This regional dialog is the book's strength. Many golden nuggets of information covering the history of the region and its potential future can be found here.

The dissertation reflects on neighboring Japan for example. Japan is a major contributor to the nonproliferation regime and as the only nation on the planet to have suffered the consequences of nuclear warfare, stands as the regime's moral conscience that would lose much should the DPRK operationalize its nuclear bombs and motivate Japan down the same road. Consider that should operationality include the targeting of the U.S. west coast, would the U.S. nuclear umbrella continue to protect Japanese territory? Even if the promise of U.S. protection was continued, would in fact the Japanese believe it to be true if the U.S. must protect itself? Does this portend a nuclear Japan and by consequence, the end of the NPT as it now stands? Such are the questions that precipitate from the richly detailed discourse found in this book.

Perhaps as enlightening as any is the chapter on China's perception of the North Korean crisis. Here, the editor is author and analyst. His studied approach reveals that Chinese policy must both prop up the North Korean regime and curtail its ambitions. China does not desire a failed regime in North Korea. It desires regional stability to reinforce its economic ambitions. A flood of North Korean refugees fleeing a collapsed nation will cause neighboring China untold problems. At the same time, advances in North Korean missile technology not to mention its nuclear armaments, threaten China's regional trading partners and in the long term may invoke a U.S. intervention in China's own backyard. Imagine for example a violent takeover of a collapsed North by the South Korean military supported by the U.S. North Korean antagonism also has the potential to drag down China's international reputation via Chinese protectionism (not so prominently displayed in recent years as exemplified by Chinese affirmations of UN sanctions against the DPRK). Consider also that the nuclear plans of South Korea, Taiwan, and, as just noted, even Japan may be influenced towards proliferation by the North's provocations the results of which may shift regional power ever so slightly away from China.

If the book has a weak point, it can be found in Chapter 9. Here, Daniel Twining (German Marshall Fund) reflects on the U.S. special nuclear cooperation agreement made with India outside the standard norms of the NPT. The questions of whether the agreement undermined the NPT regime and whether such an agreement would be a suitable model for inducing North Korea back to the fold are posed. He quickly answers no to both questions and proceeds to expound on how the Indian arrangement actually strengthens nuclear non proliferation. It is not clear why this approach to the North Korean dilemma is relevant. As Twining himself points out, these are two different nations: one which signed the NPT then pulled out of it and one with apparently deep convictions, that never signed. One has a track record connecting it to A. Q. Khan's underground nuclear supply chain and one that has utilized a Canadian reactor supplied strictly for peaceful purposes in 1954 to construct a military nuclear program—but has by and large, complied with most international nuclear norms over the decades. One is seeking regime survival while the other seeks to be a player on the world stage. Though in both instances, nuclear weapons were sought for the same reason as all other nations do: mere advantage, it is clear from the earlier chapters of the book that North Korea is playing its dangerous game in the vacuum of isolation while India, seeking economic growth and influence, chooses internationalism, trade and participation in world affairs. So what can we learn from the Indian nuclear agreement that can possibly be of assistance dealing with North Korea? The answer is precious little. Instead this chapter devolves into an argument touting the advantages of the Indian nuclear agreement. It leaves the reader wondering what a discussion of this Bush II-era handshake—largely designed to provide a bulwark to China's growing influence—is doing here.

As is well known, the U.S.-India agreement is controversial and has been challenged by non-proliferation experts on many grounds. For background on this unprecedented arrangement, seek out the paper by Leonard Weiss entitled U.S.-Indian Nuclear Cooperation, Better Later than Sooner, *(Nonproliferation Review,* Vol. 14, No. 3, November 2007). Other papers, particularly those of Sharon Squassoni, Director and Senior Fellow at the Center for Strategic and International Studies (*The U.S.-India Deal and Its Impact,* 2010 for the Arms Control Association), and George Perkovich of the Carnegie Endowment for International Peace (Toward Realistic U.S.-India Relations, 2010) also discuss the various flaws, negative repercussions and fallout of the agreement. These issues and their ramifications may still be played out on the world stage. It will be interesting to see the U.S. reaction to an Indian nuclear test (the deal abrogates – or could/should that ever occur). Although Dr. Twining's account may hold merit for many, his chapter seems oddly misplaced. It reads, at least on the face of it, as a political defense of the agreement rather than an addition to the book's discourse. It does not appear at first blush to bring significant value to a discussion about an intransigent regime so different from India's democratic system and so dead set on acquiring operational nuclear weapons with the intent to leverage them in a hazardous game of saber rattling, false promises, and threats.

All is not lost for the way forward for dealing with the DPRK is mapped out by Moore in his final summary chapter. Using the conclusions developed in the previous chapters it seems a pragmatic and realistic plan. The concepts include creation of a Japan-Korea nuclear weapons free zone, the formal ending of the Korean War by treaty, recognition of the DPRK and the opening of full diplomatic relations (in that order) to build confidence between the U.S. and the DPRK. The softening of trade restrictions on the North to allow for domestic reforms to take root is also proffered. The idea is to first build good will over time between the U.S. and North Korea, by giving the latter what it seeks so dearly. Once these "gifts" are delivered (recognition by the U.S., a formal end to the war and with it some security assurances by the

U.S.), it should prove difficult for the DPRK to back away on the contingency to the plan: denuclearization—lest it face serious international condemnation and subsequent pressure. A better domestic standard of living will also alleviate some of the embarrassing disparity between the North and South that Pyongyang expends much energy and resources on to keep secret from its populace.

This is a well-written and deeply researched volume (more than forty pages of references and nicely indexed). It is recommended for its straightforward analysis, readability and conciseness. Its international perspective lends it an exceptional level of interest that will keep the curious reader engaged. Except for the one miscue concerning India, it is a thoughtful approach that engineers, nuclear scientists, and others outside the political science world with an interest in this most important of international crises, will find accessible and useful.

End Note

1. Ironically, India's use of plutonium produced from the Canadian reactor spurred creation of the Nuclear Suppliers Group (NSG), the same group that eventually granted India an exemption from its supply restrictions in support of the U.S.-India agreement.

Taking the Long View in a Time of Great Uncertainty

Going Back to Our Roots — DOE's Nuclear Security Role

By Jack Jekowski
Industry News Editor and Chair of the Strategic Planning Committee

Several of my columns in the past couple of years have focused on the growing international activities and collaborations of the INMM, as the world has become a more complex environment with respect to "things nuclear." These efforts by the membership represent an evolutionary change that is occuring in the work of the Institute as technology shrinks the world, and "things nuclear" dominate national security strategies, hopes of future prosperity, and a more globally-consicous focus on the tenets of the Treaty on the Nonproliferation of Nuclear Weapons (NPT) established forty-five years ago.[1]

The Institute itself, however, had its origins, dating back more than fifty-five years, in the U.S. Atomic Energy Commission (AEC) and what subsequenlty became known as the Nuclear Weapons Complex, and now is known as the Nuclear Security Enterprise or NSE.[2] The NSE, comprised of the National Security Laboratories, supported by the "production" sites and the Nevada National Security Site (NNSS, formerly known as the Nevada Test Site) continue to perform "great science" not only in sustaining a safe, secure and reliable nuclear deterrent, but also in efforts to secure nuclear materials worldwide, promote peaceful uses of nuclear energy, and myriad other activities, both domestically and internationally. Over those five decades, many changes have occured, including the organizational structure of the Enterprise as well as the processes for overseeing their activities.

In the *Journal of Nuclear Materials Management* (*JNMM*), Volume II, No. 1, Spring 1973,[3] the editor, Curtis Chezem, stated the following:

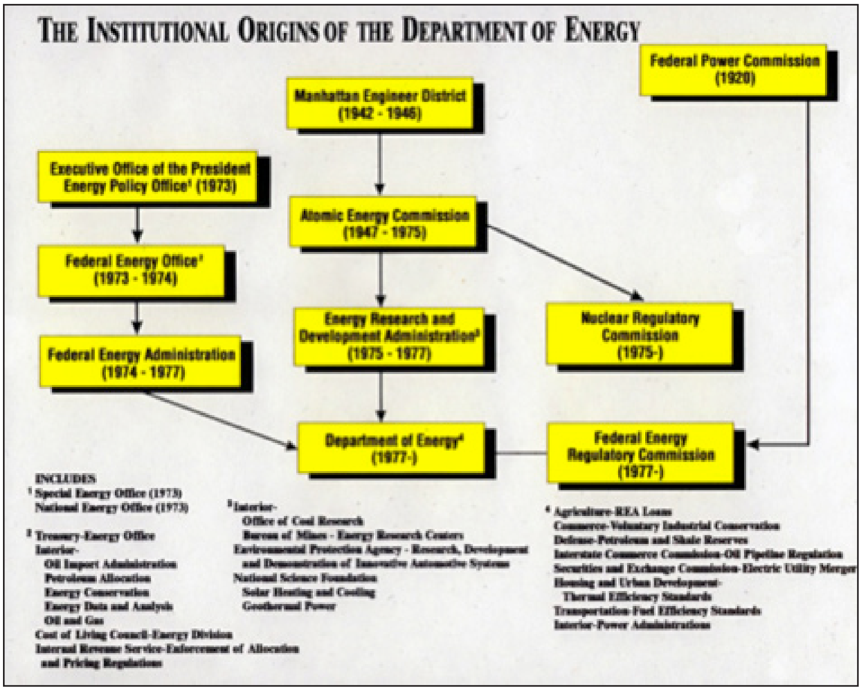
> "The most significant development during the last year has to be the upheaval in the Atomic Energy Commission."

Fast forwarding forty-two years, we can take a look around and make a similar statement concerning the state of the current Enterprise, as several major advisory panels, including some that have been congressionally commissioned, continue to examine issues, historical perspectives, and future needs, making significant recommendations for change. These issues are being driven by "externalities"[4] that surround us all of the time, not the least of which are societal changes, socio-political upheavals, economic changes, and science and technology breakthroughs.

This column is intended to serve as a forum to present and discuss current strategic issues impacting the Institute of Nuclear Materials Management in the furtherance of its mission. The views expressed by the author are not necessarily endorsed by the Institute, but are intended to stimulate and encourage JNMM *readers to actively participate in strategic discussions. Please provide your thoughts and ideas to the Institute's leadership on these and other issues of importance. With your feedback we hope to create an environment of open dialogue, addressing the critical uncertainties that lie ahead for the world, and identify the possible paths to the future based on those uncertainties that can be influenced by the Institute. Jack Jekowski can be contacted at jpjekowski@aol.com.*

History Repeating Itself?

Several timelines and histories have been published about the evolution of the NSE,[5] some of which were identified in the Taking the Long View column in the April 2012 issue.[6] Although the history of the Nuclear Enterprise has been a roller-coaster ride over the decades, with the formation of the Energy Research and Development Administration (ERDA) in 1975 out of the Atomic Energy Commission, and then the subsequent formation of the U.S. Department of Energy in 1977, and ultimately, the creation of the National Nuclear Security Administration (NNSA) in 2000 (see figure for an early historical perspective, not including the creation of NNSA in 2000), it seems as though the pace of significant change has increased in the new millennium. In recent reports, including one released in November 2014 by the Congressional Advisory Panel on the governance of the Nuclear Security Enterprise titled, "A New Foundation for the Nuclear Enterprise," it has been noted that in the last two decades more than fifty reviews and studies have examined the issues and organizational



structure of the Enterprise, as well as the challenges that have continued after the formation of the NNSA in March 2000. Each of these reports have had accompanying recommendations, with the most recent Advisory Panel providing nineteen primary recommendations and sixty-three sub-recommendations to improve performance, efficiency, and accountability.[7] Such appears to be the "nature of the beast," as the U.S., amid global changes, struggles to sustain a viable nuclear deterrent while leveraging the phenomenal talents and infrastructure of the Enterprise in difficult fiscal times.

The Role of DOE and the Laboratories in the Recent Iranian Negotiations

Despite all of the studies, reviews, and recommendations to modernize and restructure the Enterprise, the real-world mission of the U.S. national security laboratories came to light once again as U.S. Secretary of Energy Ernest Moniz prominently worked with U.S. Secretary of State John Kerry in the recent "P5+1 nuclear negotiations"[8] during the past several months to strike a preliminary deal with Iran that would pave the way for a diplomatic solution to one of the most consequential issues of the new millennium. In a recent news release,[9] Moniz acknowledged the role that the NSE played in accomplishing this challenging feat (emphasis added):

> *"The key parameters established today lay the groundwork for achieving the P5+1's objective of blocking Iran's four pathways to nuclear weapons: the two uranium pathways through Iran's Natanz and Fordow enrichment facilities, the plutonium pathway at the Arak reactor, and the covert pathway.*
>
> ***"America's leading nuclear experts at the Department of Energy and its national labs and sites were involved throughout these negotiations, evaluating and developing technical proposals to help define negotiating positions in support of the U.S. delegation.*** *As a result, I'm pleased to say that we are very confident in the technical underpinnings of this arrangement."*

And, in a related news story in *The New York Times*[10] titled "*Atomic Labs Across the U.S. Race to Stop Iran,*" the role of the various labs during the negotiations was discussed; including a side article titled, "*A Simple Guide to the Nuclear Negotiations with Iran.*"[11]

Hope for the Future

Despite the complexities of the various studies described here, and the impending changes facing the NSE in the coming years, members of the INMM Southwest Chapter were recently greatly encouraged for the future of the Institute, our laboratories, and the world, as more than thirty young students from the University of New Mexico and Texas A&M student chapters gave a day-long series of technical presentations on a wide range of topics germane to the issues the world is facing today (see photo taken outside the technical meeting venue in Taos, New Mexico, USA). The presentations ranged from new techniques to detect the surreptitious diversion of materials

from spent fuel, to forensic methods for detecting and analyzing signatures from nuclear events.

In end-of-day discussions, as everyone wound down from an intense, nonstop day of technical interactions, it was noted that the eight student presentations had given new hope to the more senior members in attendance that the "gauntlet" was being passed to a passionate and highly-educated new generation.[12]

End Notes

1. See https://www.iaea.org/sites/default/files/publications/documents/infcircs/1970/infcirc140.pdf for the full Treaty language. Of note, two Articles in the Treaty have taken front stage in international discussions recently, Article IV, which speaks to the "*inalienable right of all the Parties to the Treaty to develop research, production and use of nuclear energy for peaceful purposes without discrimination…*" and Article VI which speaks to nuclear disarmament: "*Each of the Parties to the Treaty undertakes to pursue negotiations in good faith on effective measures relating to cessation of the nuclear arms race at an early date and to nuclear disarmament, and on a treaty on general and complete disarmament under strict and effective international control.*"
2. See http://itpnm.com/whats-new-archives/whatsnew-archive-popup-may-2009a.htm for a link to a presentation by the author at the 2009 annual INMM SW Chapter Taos Technical Meeting titled "*Complex Transformation and the Future of the Nuclear Security Enterprise.*" Similar presentations are available on the transformation of the Weapons Complex since 2006 under the "What's New" link on the ITP website in the May time frame of each year.
3. See the JNMM Archive link, under the "Resources" tab, on the member's login at the INMM website – www.inmm.org
4. See Jekowski, J. 2014, "Taking the Long View in a Time of Great Uncertainty," *Journal of Nuclear Materials Management,* Volume 39, No. 1, pp. 39-41, the inaugural column describing the strategic planning effort led by Ken Sorenson, and how "externalities" played a role in developing a new organizational structure for the Institute. Also see related discussions of updated externalities in ibid, Volume 41, No. 3, pp. 20-22 ("Readjusting Priorities").
5. See, for example, http://energy.gov/management/office-management/operational-management/history/doe-history-timeline
6. Jekowski, J. 2012, "Taking the Long View in a Time of Great Uncertainty: Looking Back at a Decade of Tumult – and Looking Forward to an Uncertain Future," *Journal of Nuclear Materials Management,* Volume 40, No. 3, pp. 99-101.
7. See http://cdn.knoxblogs.com/atomiccity/wp-content/uploads/sites/11/2014/12/Governance.pdf?_ga=1.83182294.1320535883.1415285934 for the report, and http://energy.gov/seab/downloads/seab-memorandum-department-congressional-advisory-panel-governance-nuclear-security for a copy of the Secretary of Energy Advisory Board's review and comments.
8. In reference to the permanent five members of the UN Security Council plus Germany; also known as the E3+3 in recognition of the original negotiators with Iran in the early 2000s – France, Germany and the United Kingdom who met to try to diplomatically resolve the situation. See https://www.armscontrol.org/factsheets/Iran_Nuclear_Proposals for a lengthy history of the earlier negotiations.
9. See http://energy.gov/articles/statement-us-secretary-energy-ernest-moniz-p51-nuclear-negotiations for full text of news release.
10. See http://www.nytimes.com/2015/04/22/us/in-atomic-labs-across-us-a-race-to-stop-iran.html?mwrsm=Email&_r=1
11. See http://www.nytimes.com/interactive/2015/03/31/world/middleeast/simple-guide-nuclear-talks-iran-us.html
12. Jekowski, J. 2013, "Taking the Long View in a Time of Great Uncertainty: Throwing Down the Gauntlet to the Next Generation of Nuclear Stewards — the Enduring Nuclear Legacy," *Journal of Nuclear Materials Management,* Volume 42, No. 4, pp. 86-89.

Calendar

September 14–16, 2015
INMM Vulnerability Assessment Tools Workshop
Renaissance Boston
Waterfront Hotel
Boston, Massachusetts USA

October 4–7, 2015
8th INMM/ESARDA Joint Workshop
Jackson Lake Lodge
Grand Teton National Park
Moran, Wyoming USA

January 11–13, 2016
INMM 31st Spent Fuel Management Seminar
Washington Marriott Georgetown
Washington, DC USA

July 24–28, 2016
INMM 57th Annual Meeting
Atlanta Marriott Marquis
Atlanta, GA USA

September 11–16, 2016
PATRAM 2016
Kobe Portopia Hotel
Kobe, Japan

For more information, visit the INMM Events Page.

Author Submission Guidelines

The *Journal of Nuclear Materials Management* is the official journal of the Institute of Nuclear Materials Management. It is a peer-reviewed, multidisciplinary journal that publishes articles on new developments, innovations, and trends in safeguards and management of nuclear materials. Specific areas of interest include facility operations, international safeguards, materials control and accountability, nonproliferation and arms control, packaging, transportation and disposition, and physical protection. *JNMM* also publishes book reviews, letters to the editor, and editorials.

Submission of Manuscripts: *JNMM* reviews papers for publication with the understanding that the work was not previously published and is not being reviewed for publication elsewhere. This restriction includes papers presented at the INMM Annual Meeting. Papers may be of any length. All papers must include an abstract.

The *Journal of Nuclear Materials* Management is an English-language publication. We encourage all authors to have their papers reviewed by editors or professional translators for proper English usage prior to submission.

Papers should be submitted as Word or ASCII text files only. Graphic elements must be sent in TIFF, JPEG or GIF formats as separate electronic files.

Submissions may be made via email to Managing Editor Patricia Sullivan at psullivan@inmm.org. Submissions may also be made via by regular mail. Include one hardcopy and a CD with all files. These submissions should be directed to:

Patricia Sullivan
Managing Editor
Journal of Nuclear Materials Management
111 Deer Lake Road, Suite 100
Deerfield, IL 60015 USA

Papers are acknowledged upon receipt and are submitted promptly for review and evaluation. Generally, the corresponding author is notified within ninety days of submission of the original paper whether the paper is accepted, rejected, or subject to revision.

Format: All papers must include:
- Corresponding author's complete name, telephone number and email address
- Name and address of the organization where the work was performed
- Abstract
- Tables, figures, and photographs in TIFF, JPEG, or GIF formats. **Color is encouraged.**
- Numbered references in the following format:
  1. Jones, F.T., and L. K. Chang. 1980. Article Title. *Journal* 47(No. 2): 112–118. 2. Jones, F.T. 1976. *Title of Book*, New York: McMillan Publishing.
- Author(s) biography and photos
- **A list of keywords**

The *Journal of Nuclear Materials Management* does not print "foot notes." We publish references and/or end notes. If you choose to include both references and notes, you may combine them under the same heading or you may keep them separate, in which case you must use numbers for the References (1., 2., 3., etc.) and letters (A., B., C., etc.) for the End Notes.

JNMM is published digitally in full color. Color graphics and images are encouraged.

Peer Review: Each paper is reviewed by at least one associate editor and by two or more reviewers. Papers are evaluated according to their relevance and significance to nuclear materials safeguards, degree to which they advance knowledge, quality of presentation, soundness of methodology, and appropriateness of conclusions.

Author Review: Accepted manuscripts become the permanent property of INMM and may not be published elsewhere without permission from the managing editor. Authors are responsible for all statements made in their work.

INSTITUTE OF NUCLEAR MATERIALS MANAGEMENT

Membership Application

All areas marked with * are required information.

For Office Use Only

* Demographic Information

ID:

* First/Given Name: ____________ Middle Name/Initial: ____________ * Last Name/Surname: ____________

Designation: ____________ (e.g. Jr., III, PhD, MSc, etc.)

* Job Title: ____________ (e.g. Engineer, Scientist, etc. If currently a student, indicate "Student")

❑ Yes, I have been an INMM Member before now. (If held under a previously different name, please indicate here): ____________

* Institution: ____________

* Street Address: ____________

* City: ____________ * State/Province/Prefecture: ____________ * ZIP/Postal Code: ____________ * Country: ____________

* Phone: ____________ Fax: ____________ * E-mail: ____________

❑ please exclude my info from the Online Member Directory made available to INMM Members at inmm.org

* Membership

❑ Student $30 **

❑ Regular $60

**Sustaining Members

❑Type 1, 0-19 Employees $350

❑Type 2, 20-49 employees $700

❑ Type 3, 50-200 employees $1,000

❑ Type 4, over 200 employees $2,500

❑ Type 5, over 200 employees incl 3 comp Annual Meeting Registrations $5,000

Memorial Education & Outreach Fund

❑ I wish to make a contribution to the INMM Memorial Education and Outreach Fund.

TOTAL $ ____________

** Required for Student Memberships only, provide the contact information for a faculty advisor to verify your full-time student status

Name: ____________ Phone: ____________ E-mail: ____________

* Type of Organization

❑ Academia (Faculty/Staff)

❑ Consultant/Research

❑ Government or International Agency

❑ Other

❑ Academia (Undergraduate/Graduate Student)

❑ Equipment Manufacturer

❑ Military

❑ Commercial Utility

❑ Government Contractor

❑ Nuclear Material Processing

* Fields/Subjects of Expertise: ____________

* Job Description: ____________

(i.e. a brief explanation of your professional responsibilities as related to your current job title. If currently a student, indicate "Student")

* Total Number of Years Work Experience in Nuclear Materials Management Fields: ____________

* Please Number Your Top Three Areas of Interest 1-3:

___ ANSI Standards

___ Facility Operations

___ International Safeguards

___ Material Control & Accountability

___ Non-Proliferation & Arms Control

___ Nuclear Security & Physical Protection

___ Packaging, Transportation & Disposition

Membership in Other Societies: ____________

(e.g. ESARDA, WINS, ANS, etc.)

Honors/Honorary Societies: ____________

Other Experience or Training: ____________

* Indicate School — * Indicate Degree & Major — * Indicate Date Degree Obtained/Anticipated

College or University: ____________

Graduate School: ____________

Post-Graduate School: ____________

* Payment by

❑ VISA ❑ MasterCard ❑ Discover Card ❑ Diners Club ❑ American Express ❑ Check ❑ Wire Transfer ***

*** Information needed for wire transfer payment made available by request only

❑ I wish to renew my dues AUTOMATICALLY until such time as I choose to stop. (Not applicable to lifetime members. Written notice required for cancellation.) To authorize automatic renewal of your INMM Membership, simply check the appropriate box on your Membership Application. You will be charged for subsequent years' dues according to the payment information you provide. INMM will send you a reminder notice of the impending automatic debit at least one month before the charge to your account is to be made. To cancel participation in this program at any time, simply inform INMM Headquarters in writing before August 1st of the year for which you wish to cancel your participation. Thereafter, you can renew "Manually" or cancel your membership altogether.

* Card No.: ____________ * Exp. Date: ____________

* Name on Card: ____________ * Signature: ____________

* Make checks payable in U.S. dollars to: INSTITUTE OF NUCLEAR MATERIALS MANAGEMENT • PO Box 71571 • Chicago, Illinois 60694-1571 U.S.A. +1-847-480-9573 ext. 282 • Fax: +1-847-480-9282 • E-mail: tlaws@inmm.org • Website: www.inmm.org • INMM Federal Tax ID: 31-0740753