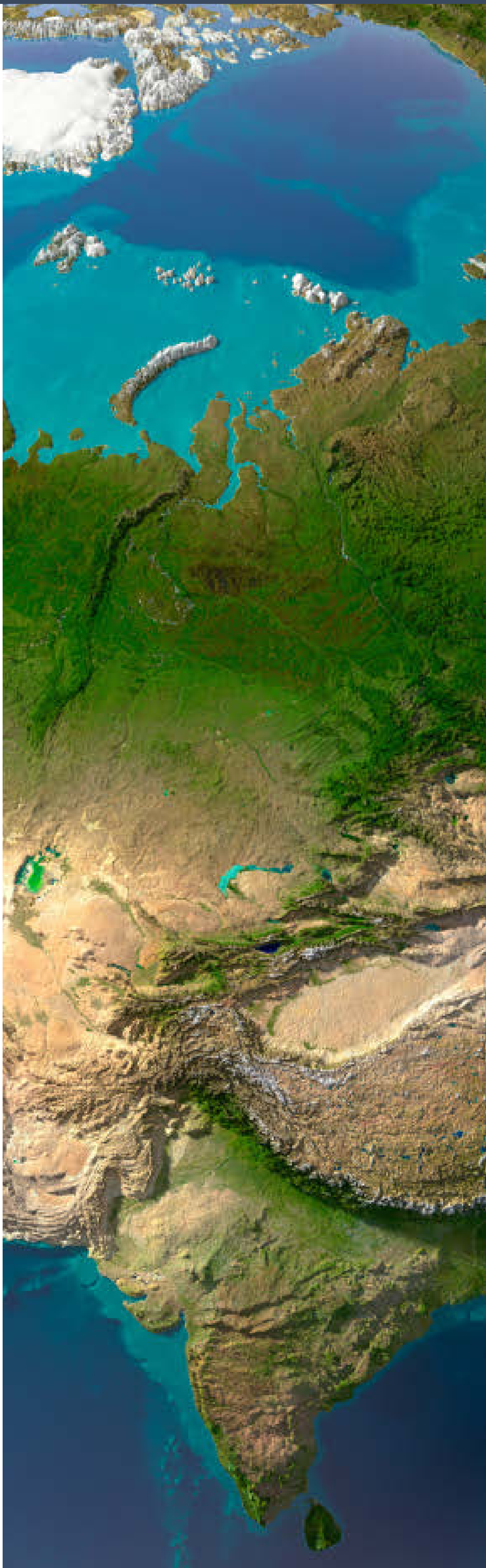
Volume XLIV, Number 2

JNMM Journal of Nuclear Materials Management



INMM
INSTITUTE OF NUCLEAR MATERIALS MANAGEMENT

Published by the Institute of Nuclear Materials Management

INSTITUTE OF NUCLEAR MATERIALS MANAGEMENT INMM

57th

Institute of Nuclear Materials Management

Annual Meeting

Save the Date!

July 24 – 28, 2016

Atlanta Marriott Marquis
Atlanta, Georgia USA

www.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 $500 per year. Single copy of the proceedings of the Annual Meeting (United States and other countries) $200. Send subscription requests to *JNMM*, One Parkview Plaza, Suite 800, Oakbrook Terrace, IL 60181 USA. Make checks payable to INMM.

DISTRIBUTION and delivery inquiries should be directed to *JNMM*, One Parkview Plaza, Suite 800, Oakbrook Terrace, IL 60181 USA, or contact Amy Lydic at +1-847-686-2236; fax, +1-847-686-2251; or email, inmm@inmm.org.

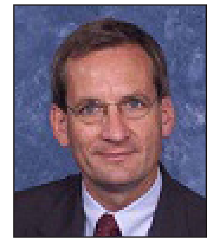
JNMM Journal of Nuclear Materials Management

Topical Papers

Institute News

Departments

INMM
INSTITUTE OF NUCLEAR MATERIALS MANAGEMENT



Preparing for "Off-normal" Situations

By Larry Satkowiak
INMM President

I look out the window and it is snowing. That is a big deal here in Tennessee (USA). We hardly ever get any accumulation of snow, so when it does snow, it is a minor crisis. Both pedestrians and drivers have difficulty coping because it is an "off-normal" situation. Leading up to our potential snow season there is a lot of talk about *best practices* regarding driving and walking safely in snowy conditions in the hope of avoiding an accident. What does this have to do with the INMM and the world of nuclear material management? The very reason why the Institute was established was to provide a forum for the development and promulgation of *best practices* all focused on nuclear material and its management. The Institute (collectively, we are the Institute) is a diverse group of nuclear material managers—domestic and international, policy and technical, governmental, and non-governmental—who develop and disseminate *best practices* in nuclear security, nonproliferation, arms control, nuclear packaging and transportation, international safeguards, material accounting and control, and facility operations. Our goal is not only to improve the general management of nuclear materials on a day-to-day basis but also assist in being prepared for "off-normal" situations. That too is a big deal—a really big deal. The nuclear materials management community is entrusted with the safe and secure stewardship of some of the potentially most dangerous, but at the same time, most useful materials in the world. It is a responsibility that the INMM and its members take very seriously.

INMM/WNTI/PATRAM Archives

In February, INMM announced the launch of an archive of PATRAM Proceedings. An excerpt is below:

The Institute of Nuclear Materials Management (INMM) and the World Nuclear Transport Institute (WNTI) are pleased to announce a close collaboration of our two Institutes that is intended to foster best practices and increased awareness in the areas of packaging, storage, and transportation of nuclear materials. The missions of the two Institutes, coupled with their geographical reach, make for a strong partnership in supporting the safe and secure packaging, storage and transport of nuclear materials. This is a focus that is becoming particularly important in emerging commercial nuclear markets.

Two near-term goals for INMM and WNTI are to co-sponsor transportation workshops in identified emerging nuclear markets and to support the continued success of the Packaging and Transportation of Radioactive Materials (PATRAM) conference into the future. With respect to PATRAM, it gives us great pleasure to announce the launching of the PATRAM Proceedings website….

This announcement, which was well-received throughout the nuclear community, is culmination of more than three years of effort by Ken Sorensen (Immediate Past President), Henry-Jacques Neau (Secretary-General, WNTI), and many others to strengthen the ongoing relationship with WNTI and reinforce the INMM's role in developing best practices in packaging, storage, and transportation of nuclear and radiological materials worldwide. Congratulations to all!

Looking Back

November Executive Committee Meeting—In November, the Executive Committee (EC) met in Seattle, Washington (USA). The November meeting's primary focus is developing and approving the operating budget for the Institute. The task is to develop a budget that reflects the goals and objectives of the Institute and its members. Periodically, it is worthwhile to do an assessment to ensure that we are meeting the needs of our members. To that end, the EC agreed to engage an outside expert who specializes in developing strategies for building and sustaining successful professional societies. The assessment/strategic planning effort was kicked off in January with the membership survey that many of you participated in. During the next few months there will be tele-

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.

phone interviews, in-person meetings, etc., with a draft product presented at the Annual Meeting this summer. Our intent is to utilize the results of this process to develop a stronger organization that meets the needs of our nuclear materials management community.

Another highlight of the November meeting was that several participants met with members of the University of Washington Student Chapter and their faculty adviser. A lively and enlightening discussion on world events ensued. I was very impressed with their breadth and depth of knowledge.

31st Annual Spent Fuel Seminar—In January, the 31st Annual Spent Fuel Seminar was held at the Washington Marriott Georgetown in Washington, D.C. (USA). Congratulations to Jeff England, the INMM Packaging, Transportation, and Disposition Technical Division, for putting together another outstanding agenda. An international group of more than 130 participants from government, industry, trade organizations, academia and professional societies presented papers, shared ideas and exchanged best practices. The proceedings can be found on the INMM website.

8th INMM/ESARDA Joint Workshop—In October, the Institute of Nuclear Materials Management (INMM) and the European Safeguards Research and Development Association (ESARDA) held their eighth joint workshop at Jackson Lake Lodge, Wyoming (USA). The overall theme was building international capacity. The workshop comprised a day and a half of intense working group meetings in four parallel sessions sandwiched between an opening plenary session filled with challenges and a closing plenary summarizing the outcomes. The topics were nonproliferation and nuclear security, arms control, international safeguards, and training. Under these topics, in the parallel sessions, each half-day was devoted to a different theme, with discussion preceded by brief position papers. Many of the papers and all of the working group summaries can be found on the INMM website.

Looking Forward

In early March, the Technical Program Committee met to review all the abstracts submitted, sort them into sessions, and develop the technical program for the 57th INMM Annual Meeting, which will be held July 24-28, 2016, at the Atlanta Marriott Marquis in Atlanta, Georgia (USA). It looks like we will have another strong program this year.

The Institute of Nuclear Materials Management, U.S. Naval Academy, American Nuclear Society and the U.S. Naval Academy American Nuclear Society Student Chapter, in association with the National Cybersecurity Institute, are pleased to announce a *Technical Meeting on Nuclear Energy and Cyber Security* to be held at the U.S. Naval Academy and the Annapolis Waterfront Hotel on April 17-19, 2016, in Annapolis, MD (USA) to recognize the first USNA graduating class of Nuclear Engineering and Cyber Security majors.

The Texas A&M Student Chapter in conjunction with the International Safeguards Technical Division and the Southwest Regional Chapter, is holding a *Safeguards Culture Workshop*, April 26-27, 2016, at Texas A&M University, College Station, Texas (USA). The intent of this workshop is to gather experts in safeguards and other related fields to explore and define what is meant by "safeguards culture," to assess the degree to which safeguards can be incorporated into the culture of an organization, and to identify research areas that need additional focus.

The 18th International Symposium on the Packing and Transportation of Radioactive Materials (PATRAM) will be held on September 18-23, 2016, at the Kobe Portopia Hotel in Kobe, Japan. PATRAM brings together experts from governments, industries and research organizations worldwide to exchange information on all aspects of packaging and transport of radioactive materials around the globe.

Finally

It has stopped snowing. However, just like in the nuclear materials management world, the need for vigilance and constant preparation never ends.

INMM President Larry Satkowiak can be reached at satkowiaklj@ornl.gov.

The Continued Relevancy of IAEA Safeguards

By Markko Koskelo
JNMM *Assistant Technical Editor*

As I write this column I remember the conversation I had with Dennis Mangan, the long-time Technical Editor of the *Journal*, several years ago. Dennis had just lost his assistant technical editor and was looking for a suitable victim (er… replacement) to help with the *Journal*. The position intrigued me and I agreed to help out. It has been fun, a challenge, and an education to learn how a professional journal like the *JNMM* is compiled for every issue. There is a very large supporting cast of Technical Division Chairs, Associate Editors, and reviewers without whom the Journal could not be done. The *Journal* is so much more than just the Managing Editor, the Technical Editor and the Assistant Technical Editor. As I write this column on behalf of Dennis, who is unable to do it at this time, I hope to be able to do justice to the hard work that goes into putting together every issue of the *Journal* and particularly this special issue on IAEA safeguards.

As noted in the introductory remarks by Tero Varjoranta, the current Deputy Director General and Head of the Department of Safeguards International Atomic Energy Agency, the IAEA continues to make a vital contribution to the international peace and security and to the peaceful use of nuclear materials and related technology. It is quite fitting that the *JNMM* publish a special issue on the IAEA and the many facets of its work from implementation to technological challenges to training the current and next generation of safeguards practitioners. I encourage you to read the many interesting articles that are contained in this special issue. I would also like to extend my special thanks to Carrie Mathews who initiated and coordinated the efforts by the INMM Vienna Regional Chapter and the INMM International Safeguards Technical Division to compile this special issue. I would also like to thank the authors who took time from their undoubtedly busy schedules to write the articles in this volume and the volunteers who contributed their time to peer review the material and offer suggestions for improving the content.

Besides reading the papers on the IAEA safeguards, please check out the book review by Mark Maiello and the column by Jack Jekowski, chair of the INMM Strategic Planning Committee and editor of Taking the Long View. Both columns speak to topics that could have been taken from the news yesterday despite the fact that they were written weeks ago.

JNMM *Interim Technical Editor Markku Koskelo can be reached at mkoskelo@aquuilagroup.com.*

Introduction to *JNMM* Issue on IAEA Safeguards

Tero Varjoranta
Deputy Director General and Head of the Department of Safeguards
International Atomic Energy Agency, Vienna, Austria

International Atomic Energy Agency (IAEA) safeguards make a vital contribution to international peace and security. They allow the IAEA to provide credible assurances to the international community that states are honoring their obligations to use nuclear material and technology only for peaceful purposes.

Preserving the effectiveness of IAEA safeguards during this time of rising demand and static budget is paramount. We are therefore working hard to improve its productivity: striving for greater efficiency without compromising the credibility of our work.

We see three main ways of doing so: firstly, by doing things more smartly and efficiently in-house and in the field; secondly, by making better use of modern technology; and thirdly, by states improving their own performance in the implementation of IAEA safeguards.

In the implementation of safeguards, a good working relationship between the IAEA and the national or regional authorities responsible for safeguards implementation is critical. The Department of Safeguards is making a conscious effort to foster and sustain cooperative partnerships with these authorities. Real progress is being made, but there is further to go.

My vision for safeguards is one in which states, including safeguards authorities, and the nuclear industry see us as value added — important partners. This is of great importance for the IAEA to continue to draw independent and credible safeguards conclusions and firmly address issues of safeguards concern.

In its efforts, the Department of Safeguards fully recognizes the importance of effective communication with the international safeguards community. This issue of the *Journal of Nuclear Material Management (JNMM)*, organized by the Vienna Chapter of INMM, contributes significantly in this regard.

I greatly appreciate the authors' commitment to this initiative, as well as the dedicated support received from the peer reviewers and the INMM editorial staff. I would also like to express my support for the important role of INMM in providing a forum for exchange of ideas and information related to IAEA Safeguards.

A Note from the INMM Vienna Regional Chapter

This issue of the *Journal* has been organized through a partnership between the INMM Vienna Regional Chapter and INMM International Safeguards Technical Division. The papers cover a range of topics, describing contemporary safeguards implementation challenges and initiatives, and touching upon on-going continuous improvement efforts of the Department of Safeguards of the IAEA. The papers written by IAEA staff have been approved for external publication by the IAEA, but reflect the views of the named authors and not necessarily those of the IAEA. Finally, the Vienna Chapter would like to thank the volunteers who contributed their time and energy to peer reviewing the articles contained in this issue of the *JNMM*.

The 2015-2016 Vienna Chapter Executive Committee (left to right): Sebastian Richet (Member-at-Large); Fabian Rorif (Treasurer); Brian Boyer (Member-at-Large); Carrie Mathews (President); Elisa Bonner (Secretary); Tom Jeffrey (Vice President); John Kinney (Immediate Past President).

IAEA safeguards implementation requires competent staff, reliable equipment and technology, and good cooperation between the inspectorate and the states. Transparency and communication by the IAEA, such as through publications like the *JNMM*, can increase awareness among potentially qualified individuals, with regard to opportunities to work at the IAEA. It can also improve the understanding of the R&D community with regard to the technology development priorities of the IAEA. Transparency and communication also strengthen the cooperative relationship between the IAEA and states.

The Vienna Chapter of INMM has been in existence since 1979, with the majority of its members being staff of the IAEA. The chapter creates opportunities for networking and professional development; encourages and facilitates publications in the *Journal of Nuclear Materials Management* and proceedings of Annual Meetings; organizes expert lectures and topical workshops; and arranges an annual science and engineering fair for middle and high school students from local and nearby international schools.

More Information about the Vienna Chapter can be found on its website at www.inmmvienna.org.

IAEA Safeguards: Delivering Effective Nuclear Verification for World Peace

The IAEA makes a vital contribution to international peace and security. Its independent verification work allows the IAEA to provide credible assurances that states are honouring their international obligations to use nuclear material only for peaceful purposes.

Why Do Safeguards Matter?

Nuclear material and technology have the potential to contribute to health and prosperity. Practically all countries around the world use nuclear applications for a variety of peaceful purposes, including food and water security, energy, industry and human health. However, nuclear material and technology may also be used for the development of nuclear weapons.

The IAEA was established in 1957 to seek to accelerate and enlarge the contribution of nuclear energy to peace, health and prosperity and ensure that assistance provided by it is not used in such a way as to further any military purposes. The IAEA pursues the non-proliferation element of its work through the implementation of a set of technical measures, or "safeguards". These serve as an important confidence building measure through which a state can demonstrate—and other states can be assured—that nuclear material and technology are being used only for peaceful purposes. IAEA safeguards help to ensure that nuclear material and technology are placed only in the service of peace and the development of humankind, while preventing its diversion and misuse. Without IAEA safeguards, there would be far less nuclear cooperation and transfer of nuclear technology.

Safeguards Legal Framework

IAEA safeguards are embedded in legally binding agreements. Pursuant to the IAEA's Statute, which authorizes the Agency to establish and administer safeguards, states accept IAEA safeguards through the conclusion of agreements with the Agency. These legal agreements are of three types:

- Comprehensive safeguards agreements (CSAs) with non-nuclear-weapon states (NNWSs) parties to the Nuclear Nonproliferation Treaty (NPT) and to regional nuclear-weapon-free zone (NWFZ) treaties;
- Voluntary offer safeguards agreements (VOAs) with the nuclear-weapon states (NWSs) parties to the NPT; and
- Item-specific safeguards agreements that are currently implemented in states that are not a party to the NPT.

The vast majority of safeguards agreements are those that have been concluded by the IAEA with NNWSs parties to the NPT. Under the NPT, the NNWSs parties have committed not to produce or otherwise acquire nuclear weapons, to place all of their nuclear material and activities under IAEA safeguards and to allow the IAEA to verify their commitments.

Additional Protocols to safeguards agreements enhance both the effectiveness and efficiency of safeguards implementation in states. The additional measures provided for in an Additional Protocol to a CSA include provisions for broader information about, and inspector access to, all aspects of a state's nuclear fuel cycle.

A state with little or no nuclear material may be eligible to conclude a small quantities protocol (SQP) to its CSA, which reduces the safeguards activities conducted in the state.

Safeguards in Practice

The purpose of IAEA safeguards is to verify states' legal commitments under their respective safeguards agreements with the IAEA. Safeguards implementation during an annual cycle comprises four fundamental processes:

1. Collection and evaluation of safeguards relevant information. The IAEA collects safeguards relevant information about a state and processes and reviews it in order to evaluate its consistency with the state's declarations about its nuclear programme and other safeguards relevant information available to IAEA.
2. Development of a safeguards approach for a state, which includes the safeguards measures to meet the concrete technical objectives for verifying the state's declarations.
3. Planning, conducting and evaluating safeguards activities. The IAEA develops a plan specifying the safeguards activities to be conducted both in the field and at Headquarters. Once an activity has been conducted, the IAEA evaluates the extent to which it has attained the technical

objective(s) and identifies any inconsistencies necessitating follow-up activities.

4. The safeguards conclusions drawn by the IAEA, which are based on its independent verification and findings, are the final product of the annual safeguards implementation cycle. The conclusions provide credible assurance to the international community that states are abiding by their safeguards obligations.

Current Trends

The number of nuclear facilities coming under IAEA safeguards continues to grow steadily. So does the amount of nuclear material to be safeguarded.

Over the past five years, the number of nuclear facilities under safeguards has risen by 12 percent and the quantity of nuclear material under safeguards by some 14 percent. Demands are also increasing as more facilities are decommissioned because this generates additional needs to verify nuclear material packaging, movement and disposition. The number of states with safeguards agreements and additional protocols in force is also rising.

IAEA safeguards will need to keep adapting. Further improvements and optimization are necessary to guarantee effective, reliable and credible safeguards. It is essential that the IAEA continue to strive for greater efficiency without compromising effectiveness. With the support of its member states, the IAEA will continue to live up to the expectation of the international community by verifying the peaceful use of nuclear energy, thereby contributing to the non-proliferation of nuclear weapons.

Recent Developments in Performance Management in the IAEA Department of Safeguards

Van Zyl de Villiers, Marguerite Leonardi, Carrie Mathews, Jenni Rissanen, and William Stanley
Department of Safeguards International Atomic Energy Agency, Vienna, Austria

Abstract

This paper describes recent developments under an initiative begun in 2014 to improve the measurement of performance by the International Atomic Energy Agency (IAEA) Department of Safeguards. The approach taken and progress made over the past year to further develop the performance management support tool and the more recent work to "pilot test" selected performance indicators are described. Ultimately, the performance management tool should enable the Department to (a) monitor, evaluate, and report on the achievement of its strategic and operational objectives, and (b) improve its performance on a continual basis. The performance management tool will be aligned with related results-based management processes in the Department and the IAEA as a whole, such as strategic planning, programming, and budgeting and reporting, and will be integrated with existing and planned management systems. (This paper provides an update to a paper delivered by Van Zyl de Villiers at the 2014 IAEA Symposium on International Safeguards, which described the early activities and plans of the Departmental working group that was established for this initiative.)

Background

The International Atomic Energy Agency (IAEA) has been implementing results-based management since 2000. This includes strategic planning, risk management, biennial planning, and periodic reporting of progress and achievements through performance indicators on the implementation of the program and budget. However, in recent years it has become evident that the Department of Safeguards should improve its ability to monitor its performance and report on this to stakeholders such as the IAEA Board of Governors and member states. The existing mechanisms have been regarded as insufficient, especially given the challenge of a growing number of facilities and increasing quantities of nuclear material under safeguards and resources that remain largely at the same level. This means that increasing attention must be paid to ensuring that a high level of effectiveness can be sustained and that resources are used in an ever more efficient manner. Even though performance data is periodically collected and provided to external stakeholders through the IAEA's established program and budget reporting processes, the Department's management team requires such information more frequently and sometimes with a differentiated focus to support decision making, prioritization, and to bring early attention to potential emerging implementation challenges. The need for such real time management information is highlighted by the IAEA's dynamically changing operating environment.

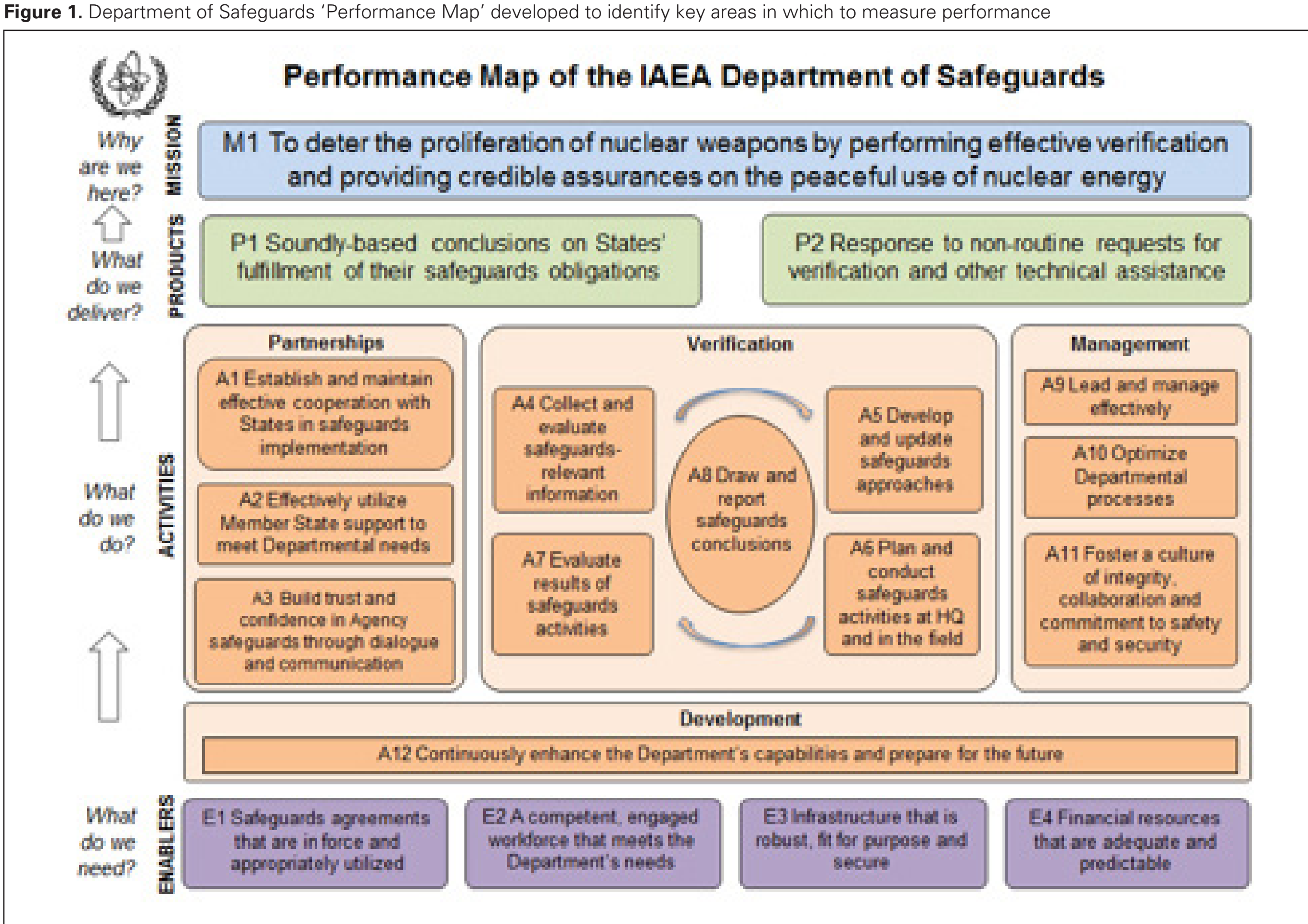
Methodology

For the reasons stated above, a Departmental initiative began in early 2014 to develop a performance management support tool for the Department. A representative Performance Indicators Working Group (PIWG) was established with a mandate from senior management to develop a flexible instrument for enhanced performance management (PM). Requirements for such a tool included: (1) ease of use, (2) avoidance of any additional burden on line management; (3) facilitation of decision making at different organizational levels; and (4) accurately reflecting performance at any point in time.

Initially the PIWG focussed on two activities, namely confirming the objectives to be achieved by the Department and compiling an inventory of indicators already in use. The former effort established the basis for setting performance targets and for monitoring, evaluating, and reporting actual achievements. The latter activity sought to identify existing performance indicators (PIs) that might meet the criteria for use in the performance management tool. Results of this analysis showed that most of the PIs in use reflected operational statistics rather than performance related information for the Department as a whole. Existing indicators were not balanced in terms of linkages to the Department's objectives, processes followed within the Department and organizational levels covered. It was also found that the typical time span covered and the frequency of measurement of the majority of indicators did not support short term decision making. The indicators were also "lagging" in nature, i.e., showing data only after the fact, and therefore did not support taking preventive action. Indicators used for reporting to member states every two years were not necessarily useful for internal management decisions or to serve as an early warning system. Thus it was clear that the existing indicators would need to be carefully reviewed and additional performance indicators would need to be developed to support a more comprehensive performance management tool.

In parallel to this initial stocktaking exercise, current practices and approaches in the field of PM were investigated. The characteristics of good performance indicators were determined and ways in which such indicators could be developed were investigated. Best PM practices were reviewed, with specific emphasis on non-profit organizations.[1] Consultations were conducted with the IAEA Standing Advisory Group on Safeguards Implementation (SAGSI) and external performance management specialists. As the PIWG's understanding of PM developed and the different levels of objectives and outcomes to be achieved were confirmed, alignment with other IAEA and Department planning and reporting processes were further reviewed. As could be expected, it was confirmed that synergy should be pursued between the PM initiative and the IAEA's results-based management processes, as specifically embodied in the biennial Program and Budget activities and the Agency's Medium Term Strategy.[2] In this regard, the Department incorporated some preliminary results from the PIWG's work into planning for the 2016-2017 biennium.

Figure 1. Department of Safeguards 'Performance Map' developed to identify key areas in which to measure performance



After reviewing good practices in the field of PM, the PIWG selected a model designed for public sector and non-profit organizations, and involved an external consultant to facilitate a two-day workshop in which the PIWG developed a departmental "performance map." A performance map is a simplified representation of the linkages between the mission of an organization (Why are we here?), the high-level outputs or products (What do we deliver?), the activities performed (What do we do?), and the resources or "enablers" required (What do we need?). The map provides a framework for the measurement of departmental performance in all of the elements as indicated (see Figure 1).

The starting point in the workshop was therefore the mission of the Department of Safeguards and the strategic and generic objectives relating to safeguards implementation. Activities of the Department were grouped with regard to safeguards implementation, collaboration and partnerships with states and other external stakeholders, effective management processes, and preparing for the future. The main components of the required resources were identified to be safeguards agreements with member states, human resources, infrastructure, and financial resources. The resulting map reflects a balanced scorecard approach to holistic organizational performance. It is a one-page representation of the overall objectives of the Department, the products to be delivered, activities to be performed and the resources and other enablers required to carry out those activities by the Department.

The consensus approach that was followed by the PIWG in the workshop and all activities to follow has played an important role in the development of a better understanding of performance management in the Department. Regular interactions between working group members and divisional management teams assisted greatly in obtaining representative inputs from internal stakeholders and developing buy-in on the process being followed towards the establishment of the envisaged PM support tool. Several iterations were required before reaching agreement on the language used in the map and its accompanying narrative, which explains more fully what is captured in each of the boxes on the map. Performance Map element owners were identified from among the members of the PIWG and assigned responsibility for incorporating the results of the workshop into an initial set of key performance questions (KPQs) and associated indicators for each element. These efforts are described in the following section.

Key Performance Questions and Performance Indicators

KPQs are designed to capture the essence of what needs to be known to ensure that the organization is performing well on the specific component of the map. Only thereafter can PIs be selected that would provide the answer, or parts of the answer, to the question. The set of PIs associated with a particular KPQ should complement one another so that the most important features of the topic are covered. In this manner, the PIs will accurately reflect the level of achievement relating to each main aspect of the Department's operations.

During the workshop, the characteristics of good KPQs were described and for each element on the map, the group developed up to three KPQs. It was agreed that KPQs should be open questions designed to stimulate discussion and force reflection by management on the map element being addressed. Closed questions (yes or no) do not adequately inform performance related management decisions or prioritization. For example, taking the map element A1 that deals with cooperation between the IAEA and states in safeguards implementation—a closed question might be "Is the IAEA cooperating effectively with states in safeguards implementation?" A more meaningful open question could be, "To what extent do states and the IAEA cooperate in conducting in-field verification activities?" or "How satisfied are states with their cooperation with the IAEA?"

Once KPQs were defined for each map element, a set of one to three PIs were then identified for each KPQ. Reaching agreement among the PIWG members of the final KPQs and associated PIs took many iterations. A second workshop was held with the consultant to examine the initial KPQs and PIs, and to evaluate the PIs against a set of criteria (see Figure 2) using an approach recommended in Reference 1. The PIWG was subdivided into smaller working groups, with each group assigned seven to eight KPQs and associated PIs. The groups were purposely composed of staff from differing organizational units to encourage challenging and critical questioning of the validity of identified KPQs and PIs. They were required to evaluate each KPQ and PI in detail (based on the template in Figure 3) and to consider the data collection sources and methods. Their results were provided to the element owners, i.e. the 'experts' on that particular element, who were responsible to review the results with relevant colleagues and produce a final evaluation for each PI.

Table 1. Examples of KPQs and associated performance indicators for pilot testing

Performance Map Element	KPQ	PI Name	PI Definition
A6. Plan and conduct safeguards activities at HQ and in the field	To what extent do the activities recorded in Annual Implementation Plans (AIPs) address the identified technical objectives?	AIP activities meeting technical objectives	The number and percentage of states with approved state-level approaches for which all technical objectives are addressed in AIPs
	To what extent were the planned activities performed?	AIP completion rate	Percentage of planned in-field activities in approved AIPs completed; percentage of state evaluation documents completed
E4. Financial resources that are adequate and predictable	To what extent is funding adequate to fulfill our mission?	Funding gap	Gap between first regular budget proposal and approved budget
	To what extent is funding adequate to fulfill our mission?	Rate of expenditure	Planned expenditure compared to actual expenditure
	To what extent is funding predictable?	Funding mix	Funding mix (regular budget, extra-budget, unfunded) in budget proposal compared to mix reflected in actual expenditures

This approach very effectively tested and critiqued the PIs, and identified those that were suitable for use in a pilot test wherein the data would be collected and performance results produced and visualized in a dashboard. In order to qualify for the pilot test, a PI had to be well-defined, the data collection method had to be in place (or could be established relatively easily), the likelihood of inducing counter-productive behaviour had to be low, and the cost/effort to evaluate the PI had to be reasonable.

Some examples of KPQs and associated PIs are shown in Table 1.

An important aspect of the pilot test was to demonstrate the ability of the data collection and analysis methods to produce meaningful performance information. In cases where multiple PIs were tested to answer the same KPQ, it was important to determine how the results could be aggregated to visualize the status of performance relating to a particular element of the map. Dashboards sometimes use traffic light analogies, color coding, gauges, dials, or other techniques to communicate the performance in an area. These require algorithms, performance targets, thresholds and other metrics to be determined, with which to decide how to convey the aggregated performance. During the pilot testing period, different approaches to visualization were compared to determine those that would best meet Departmental needs.

Figure 2. Evaluation template to test performance indicators (based on Reference 1)

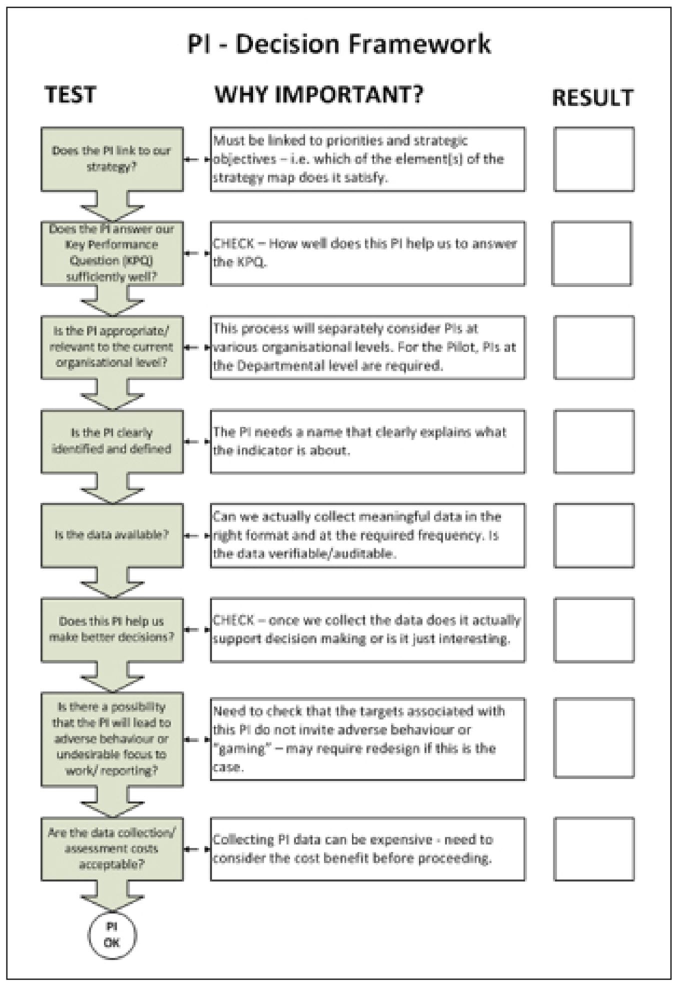


Figure 3. Detailed assessment framework for performance indicators (based on Reference 1)

Performance Indicator (PI) Design Template	
Why do we need this indicator?	
Name and definition	Clearly identifiable name and unambiguous definition
Strategic element being assessed	Description of the PI and what question this PI will help to answer
Owner of the strategic element	Identify the person(s) or function(s) responsible for the strategic element or objective
Key performance question	List the KPQ this indicator is helping to answer
Target audience	Indicate the target audience for this indicator (DDG/DIR/SH/All)
Decisions supported	List the decision(s) this indicator is helping to support
How will the data be collected?	
Data collection method	Brief description of how the data is collected
Data Source	Source of data used
Formula/Scale/Assessment	Identify the formula or scale used (%, Number of items)
Frequency	How often is the PI measured?
Who measures/reviews the data?	Name the person (role) who collects, updates and reviews this data
Expiry/Review date	Identify until when this indicator will be collected or when it will be revised
What are the targets?	
Target/Performance thresholds	Identify targets, benchmarks, thresholds
How good is the indicator?	
Cost estimate	Estimates of the potential costs incurred by introducing/maintaining this indicator
Confidence level	Provide an evaluation of how well this indicator is able to measure what is intended (good, fair, poor)
Possible dysfunctions	Note down any possible ways that this indicator could lead to adverse behaviour
Who will see the data? How will it be presented?	
Audience/Access	Who receives the reported information? Who has access to it (confidential)?
Reporting frequency	How often is this PI reported?
Reporting format/Channels	Identify format for reporting (numerical, tabular, graphical, text) and channel (report/meeting/online)
Notifications/Workflows	Identify any notifications, email alerts and workflows triggered by this indicator

Path Forward

During the second half of 2015, a selected number of PIs were pilot tested, including the first measurement thereof in order to provide experience that could be extended to the rest of the PIs that had been proposed. Some of the PIs required inputs from member states and a questionnaire was being developed for this purpose.

An important effort underway in the Department that is relevant to the performance management initiative was the updating of the Departmental long-term strategic plan. The original plan, developed in 2010 and covering the period 2012 to 2023, was being reviewed and updated, taking into account the work of the PIWG in the framework of the performance map. A close alignment of the process to update the strategic plan with the continued development of the performance management system was regarded as essential, to ensure that performance management would measure the implementation of the strategic objectives articulated in the plan. In turn, the PIs developed by the PIWG would help monitor and evaluate progress towards the plan's implementation — and inform the Department if the actions identified in the plan are not delivering as intended, thereby helping to identify the need for adjustments.

Another relevant effort was the MOSAIC project to modernize the information technology of the Department of Safeguards. This project will make safeguards-related data more accessible, and create opportunities for better use of the data for the applications to be developed in support of safeguards implementation processes.

The performance map necessarily reflects activities at the Departmental level. Performance should also be measured at lower levels, and it is essential that such performance is connected to the Departmental level map. Therefore, as a future follow up, the map will be "cascaded" into the divisional or section levels of the organization, reflecting the aspects of the Department's work that are performed by that section or division. Mechanisms will need to be developed to ensure continued connectivity between the cascaded maps and the Departmental map.

Finally, no performance management system can succeed without the support and commitment of management at all levels and the involvement of all staff members. Throughout the work to date, the Department's senior management committee had been periodically briefed and their guidance was incorporated into the work of the PIWG, including in the final version of the map. The PIWG members also kept their respective divisions informed and solicited inputs in all stages of the work. The work was also presented at suitable Departmental forums to inform all staff of the performance management initiative, explain the benefits and potential impacts, and encourage their involvement and contributions.

Lessons Learned to Date

The process described above was found to be challenging but worthwhile in raising the profile of performance management and increasing understanding of the underlying principles. It also emphasized the importance of alignment between different management and reporting processes and of buy-in by all stakeholders.

The pilot confirmed the importance and, in some cases, the difficulty of formulating clear, unambiguous definitions for performance indicators so that credible measurements can be made and performance can be tracked over time. Data sources were not available for all selected indicators, especially those that were not based on operational statistics but required qualitative inputs. The design of a performance dashboard proved to be important, but could only be done after sufficient agreement had been reached on the selected performance indicators and suitable ways in which results could be reflected.

Overall this has been a positive experience for the Department of Safeguards and can be expected to make a significant contribution to improve performance on a continuous basis.

Bibliography

1. Marr, B. 2009. *Managing and Delivering Performance*, Butterworth-Heinemann, England.
2. IAEA Medium Term Strategy, 2012-2017. http://www.iaea.org/about/mts.
3. Marr, B., and J. Creelman. 2014. *Doing More with Less* (2nd ed.), Palgrave Macmillan, Hampshire.

Organization Culture and Leadership in the Department of Safeguards

Srilata Rao
Management Advisor to the Deputy Director General, IAEA Department of Safeguards, Vienna Austria

Culture eats Strategy for Breakfast *– Peter Drucker, founder of modern management*

Abstract

Currently, the International Atomic Energy Agency (IAEA) Department of Safeguards is facing unprecedented challenges in the form of an increasing workload and a rapidly changing external environment while maintaining a relatively static level of resources. Under these demanding circumstances, it is imperative that staff in the Department feel motivated to perform their best. Contemporary research in organizational behavior shows that this can be achieved through nurturing an organizational culture where staff feel treated fairly, are recognized for their efforts and achievements, and are provided with opportunities for improving their skills and expertise that will help in contributing to their professional growth and career advancement. In addition, studies done suggest that staff perform best when being directed, guided and mentored by competent, communicative as well as compassionate leaders. To enhance such leadership qualities and establish a sustainable organizational culture within his Department, several initiatives were launched by Tero Varjoranta, the current Deputy Director General of the IAEA Department of Safeguards. This paper provides an overview of the initiatives that were introduced and implemented since October 2013, the results achieved so far, as well as the imperatives for the future.

Introduction

The International Atomic Energy Agency (IAEA) was established in 1957 to seek to enlarge the contribution of nuclear energy to peace, health, and prosperity of humankind. IAEA safeguards help to ensure that nuclear material and technology are placed only in the service of peace and development of humankind, while preventing its diversion and misuse to further any military purposes. This activity is performed by the IAEA Department of Safeguards.

At the end of 2014, the IAEA Department of Safeguards employed about 850 people from ninety-five countries. At this point in time, more than 193,500 significant quantities of nuclear material and some 1,300 nuclear facilities and locations outside facilities (LOFs) were under IAEA safeguards.

Figure 1. IAEA Safeguards in 2014 - Key Facts

Figure 1 provides a snapshot of the magnitude of the IAEA safeguards activities in 2014.

In recent years, funding for the IAEA has not kept pace with the growing demand for its services in all areas of work including safeguards. There is therefore a need to constantly find ways of increasing efficiencies without compromising effectiveness.

The Department had therefore developed a long-term strategic plan to address these growing demands for its services. However, no strategy can succeed without an understanding of the culture within which it is going to be implemented. An organization's culture can be a powerful and often invisible force that counteracts and resists attempts to change and adapt, no matter how sound the strategy may be.

In his seminal work on the subject, Schein[1] offered a definition of organizational culture as: "a pattern of shared basic assumptions that the group learned as it solved its problems of external adaptation and internal integration, that has worked well enough to be considered valid and, therefore, to be taught to new members as the correct way to perceive, think, and feel in relation to those problems."

To make organizational culture more visible, Schein devised the "onion model," which unpacked culture into three distinct layers.[2] Schein postulated that the outer layers are relatively easy to change and adapt while, in contrast, the inner layers are relatively hard to diagnose and adjust.

The outer-most layer, "Artifacts and symbols," comprises visible things such as:

- Architecture and physical surroundings
- Products and technologies
- Style (dress code - art - publications)
- Published values / mission statements
- Myths / stories / rituals/ heroes

The middle layer, "Espoused Values," comprises the values championed by the organization's leadership while the inner-most layer, "Assumptions," comprises underlying (and often unconscious) determinants of an organization's attitudes, thought processes, and actions.

Alternatively, an organization's culture can be thought of as an iceberg with the visible symbols being a mere fraction of the depths and solidity that is invisible to the eye.

When he took charge in 2013, the current Head of the Department of Safeguards, Tero Varjoranta, was fully cognizant of the importance of nurturing a suitable organizational culture in order to achieve the challenging goals ahead.

Changing organizational culture at the invisible levels is significantly challenging. It is relatively more feasible to address the here and now or the more visible aspects of culture that would also be referred to as "organizational climate." If culture is the personality of the organization, then climate has more to do with the mood or prevailing atmosphere within the organization. The climate is prone to more short-term fluctuations and is determined by many factors including leadership, structure, rewards, and recognition.

With this in mind, several initiatives under the banner "Management Matters" were commissioned by Varjoranta to diagnose the existing Departmental climate and leadership capacity, based on which specific interventions were designed and implemented to help create a more conducive climate and to enhance staff engagement.

Setting the Stage

In creating an atmosphere within the Department that would be open to giving and receiving constructive feedback, Varjoranta offered himself as the first leader to undergo an assessment process on his leadership qualities and performance. As a result, a brief survey was created and sent to the colleagues who worked most closely with him. The results of this survey were shared in detail during a staff meeting of the Department. This level of openness and sharing was appreciated by the Department and set the stage for subsequent initiatives.

In attempting to understand the various facets of the Department's climate, there was a need to identify and adopt appropriate tools and techniques which had the necessary validity[3] and reliability.[4] In some cases, such widely tested tools were available while in other cases, specific tools were created and tested internally prior to their implementation.

Departmental Culture (Climate)

Diagnosis Phase

Culture is made up of tangible and intangible elements, with many of the latter being difficult to measure and track. One of the most widely used and well-accepted methods to gather information about the tangible aspects of culture (climate) is the survey or questionnaire.

The last staff survey had been carried out in 2004 across the IAEA. It therefore appeared to be an opportune time in 2014 to conduct a survey within the Department of Safeguards to gather information on staff perceptions of the various issues that affected their engagement, motivation, and morale and to compare the changes over the decade.

Using the 2004 survey questions as a baseline, a series of discussions were held with Departmental representatives of the IAEA Staff Association[5] in order to identify the main issues affecting the staff in the recent past. These issues were then distilled in the form of twenty-one multiple-choice questions covering a spectrum of areas such as feeling of well-being, fairness, transparency, professional and career development opportunities, health and safety, and so on. In addition, respondents were provided space for comments.

The survey was administered online using a commercially available web-based software and staff members were given one month to complete it. The survey was completely anonymous; however respondents were encouraged to provide some demographic information on a purely voluntary basis to enable further analysis.

The survey had a response rate of 80 percent with more than 175 free-format comments received. The responses and comments were analysed at the Departmental level as well as at the level of the various individual divisions. Any significant differences in the level of response by division or other demographic factors (gender, length of service, type of contract) were noted for further analysis or investigation.

While the overall employee engagement score[6] was extremely positive at 87.9 percent, the responses to several questions as well as the comments nevertheless revealed some dissatisfaction and concerns on a wide range of areas such as career prospects, long-term well-being of staff, and certain management practices. Figure 2 provides an illustration of some of the topics raised in the comments.

In order to delve deeper into these areas of dissatisfaction, a series of six focus group discussions were held. These sessions were facilitated by an external consultant in order to create a "safe space" for staff members to share their opinions openly. The discussions were held under the Chatham House Rule.[7]

In preparation for these focus groups, the facilitator immersed himself in the survey results and gathered significant qualitative and trend information on the various issues troubling staff members through in-depth discussions with Departmental representatives of the IAEA Staff Association, the IAEA's human resources function, the staff counselor, and the internal investigator.

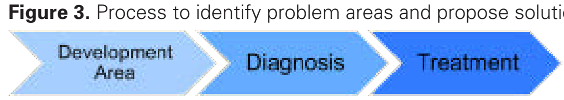
Almost eighty staff members (approximately 10 percent of the Department) from all divisions and levels participated enthusiastically in these two-hour long focus group discussions

Figure 2. Illustrative word cloud of survey comment topics

on the following questions:

- What are specific examples of Departmental management practices that need to be improved?
- What recommendations do you have to improve these specific practices?
- What leadership competencies are missing?

Figure 3. Process to identify problem areas and propose solutions



As a result of these intense discussions, the facilitator was able to identify and compile suggestions and ideas from staff members on several areas using the process illustrated in Figure 3. However, the extent to which the Department had the ability to influence these areas varied widely from little to no influence to a high degree of influence.

Those that fell in the former areas were subjects related to policies and practices that affect the entire IAEA or in some cases, the wider United Nations system. While recognizing these limitations, the Department's management decided to focus on those areas where there was the ability to exercise a greater degree of influence. Such areas included the strengthening of management and leadership capacity, improving accountability, enhancing multi-cultural sensitivity, and so on.

Implementation Phase

A management retreat was held for the Departmental senior management (Deputy Director General and his team of Directors) to engage more closely with the results of the survey and to develop an action plan to address several of the areas of concern.

Based on the discussions during the retreat as well as the inputs from the focus group discussions, several priority areas were identified and a series of actions were planned and implemented in the following areas:

- Enhancing the feeling of well-being amongst staff
- Prioritization of activities to reduce excessive workload
- Career development: through internal mobility and reassignment
- Health and safety: Developing policies, training, and tools

As mentioned earlier, it is relatively much more feasible for leaders to influence organizational climate than culture in the form of designing and improving work practices, recognizing and rewarding performance, and handling conflict in a constructive manner. With this in mind, the leadership development initiative was launched so that persons in leadership roles within the Department were provided with an enhanced awareness of the necessary skills and tools to bring about positive changes in the organizational climate of the Department of Safeguards.

Leadership Development

A wide-ranging study carried out by McKinsey & Company in 2012[8] showed that chief executive officers and business unit heads across industries firmly believe that leadership drives performance. Over 90 percent of those surveyed in this study were already planning to increase investment in leadership development within their organizations because they saw it as the single most important mechanism to enhance organizational performance and productivity. The Agency shares this belief, as

Figure 4. What is leadership?

evidenced by its "Leadership Blueprint" advocated by the Director General and senior management in guiding the behaviours and values of the organization.

While definitions available for the term "leadership" and discussions on its difference from "management" abound, the Department of Safeguards adopted a definition based on the hierarchy and nominated persons in Director and Section Head positions as "Leaders." Figure 4 illustrates one commonly understood definition of "Leadership."

Diagnosis Phase

Within the IAEA, a competency model comprising seven competencies had been in use for several years to assess candidates being recruited to leadership positions, i.e., Director and Section Head level positions. These competencies are:

- Analytical and Strategic Thinking
- Communication
- Change Orientation
- Decision-making
- Program and Individual Performance
- Knowledge Management
- Teamwork/Relationships

Each of these competencies had three proficiency levels of increasing progression, viz "Specialist," "Facilitator," and "Leader" levels.

For the purposes of the leadership development exercise, the description of the "Leader" level was used.

The assessment was carried out using the Occupational Personality Questionnaire (OPQ32),[9] a work-styles assessment for managerial and professional staff that provided objective information to enable better selection and development decisions.

The same competency model and tool were adopted to carry out the Leadership Competency Assessment for the staff in leadership positions in the IAEA Safeguards Department. This was complemented by a structured interview with a psychologist for each participant. These were used together to assess the proficiency level of the entire leadership group.

The group results were plotted using an innovative tool known as "Talent Maps" displaying the comparison between the results of all the participants of the competency assessment process.

These visual maps (as shown in Figure 5) are based on an algorithm developed at the University of Zürich[10] that enables visualization of objects based on their similarities. An iterative approximation algorithm finds the best solution on how various objects can be displayed on a two-dimensional map while giving a wealth of information about their similarity and the depth of certain characteristics. These maps have neither x- nor y-axes. The proximity of the objects on the map shows the degree of similarity between them while the depth of the colors represents the fit of each object to a certain set of criteria. The use of this tool was pioneered in the field of competency assessment with this exercise whereby the results of the participants' assessment against each of the seven competencies were mapped.

Each talent map was able to depict several dimensions of information in an easy-to-understand manner by providing a visual representation of the relative strength or weakness of each participant in comparison to the average on a particular competency, the clustering of staff based on the similarity of their overall personalities, and finally, the aggregate strengths and weaknesses of the group.

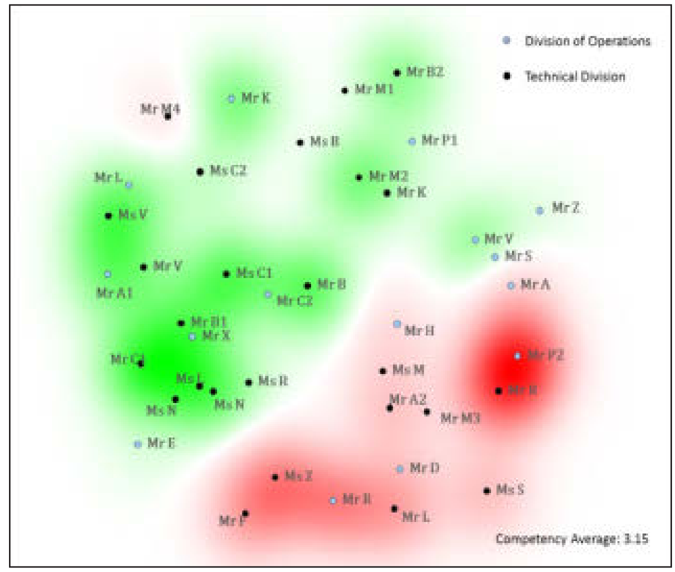
In addition to the aggregated group results, each participant received an individual report detailing his or her assessment against the seven competencies.

Implementation Phase

The first step in this phase required the participants to go through a series of development workshops to understand their own individual results and to identify those areas where they would need further support to enhance their skills and abilities.

Based on this exercise, the main areas of development for the group were identified as: communication, decision-making,

Figure 5. Illustrative talent map for one competency



and change-orientation. A custom-designed training program was then created keeping in mind the current challenges facing the Department at that point in time, i.e., the implementation of the complex MOSAIC[11] Information Technology system and the further development of safeguards implementation at the state-level.[12] A three-day leadership seminar was conducted on a pilot basis for twelve participants using case studies, role-plays, and other participatory approaches. The seminar was designed to provide a safe space and a judgment-free opportunity for participants to experiment with different skills and behaviors as a first step towards enhancing their competencies.

The seminar was well-received by participants (see Figure 6) who found the exercises very useful as it provided them with a good balance of theory mixed with ample opportunity to practice new skills. They also appreciated the principles and approaches in communication and negotiation provided by the trainers. Several participants found the tips on public speaking and making presentations very useful and immediately applicable. The examples of managing conflict and mediating claims were also found to be extremely relevant to their daily work.

Some of the key learning of the program included: (i) be simple, straightforward, convincing, and always respectful in your communication; and (ii) dealing with people is difficult: stay open and sensitive to people and their cultural background while furthering the organization's objectives.

Although the training was highly appreciated by the participants, there remained the risk that the lessons learned from the experimental situations of the seminar would lapse once

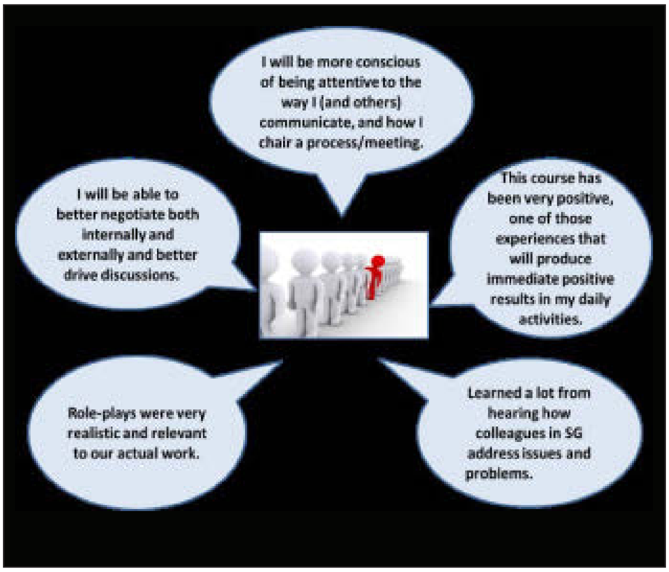


Figure 6. Feedback from Leadership Seminar

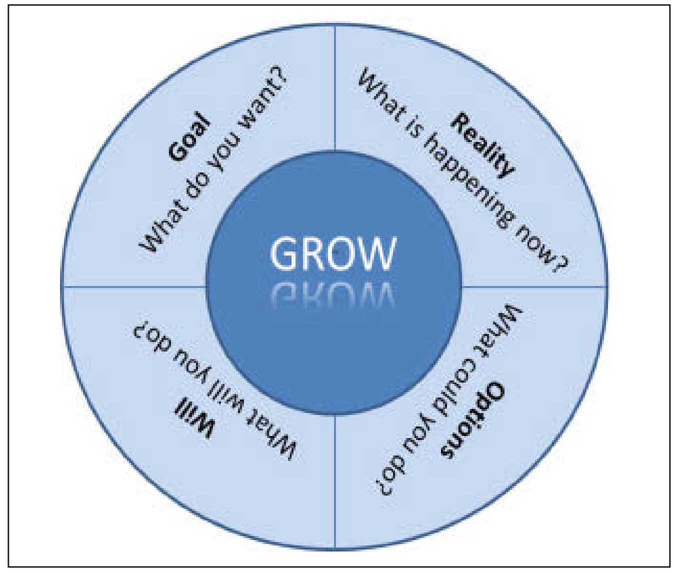


Figure 7. GROW Model of Coaching

they got back to the demands of their work place. One concern was that the participants could slip back into their professional "comfort zones." In order, therefore, to maximize the benefits gained during the training and to set up a mechanism by which participants would continue to be challenged in their assumptions and their routine behaviours, an executive coaching program was instituted.

Executive Coaching

Executive coaching is a technique for enhancing a leader's skills through targeted support to address some specific challenge being faced by the individual. As this is based on the application of knowledge and practising new skills, it is expected that such experiential learning creates a deeper understanding than one that is based on teaching.

Leaders at a higher level in an organization are expected to manage themselves without too much support or oversight from their managers. They frequently have to make difficult decisions within a limited timeframe using available information. These situations can feel quite lonely and stressful for the individual. To manage such situations, it is useful to get an external coach. Sportspersons, corporate leaders, and politicians increasingly have coaches today. It is no longer perceived as a sign of trouble if a top executive signs up for coaching. Rather, it is viewed as a necessity.

The increase in the use of coaching for leaders in private industry as well as the public sector can be attributed to the greater demands of managing global, more diverse teams in uncertain environments that are also more technologically challenging. This is exactly the scenario that leaders in the Department of Safeguards find themselves in. Leaders today are expected to quickly deliver results while managing complex tasks handled by staff members of varied backgrounds and talents from all across the world.

Coaching therefore, is not a single event; rather it is a series of interactions focused towards improving a particular skill or set of skills.

The first executive coaching cohort within the Department of Safeguards consisted of twelve participants, all at director or section head level. The executive coach, a qualified and extremely experienced professional, used the GROW model of coaching (see Figure 7), which stands for:

- G: Setting a GOAL for the coaching;
- R: Assessing the Reality of the situation;
- O: Examining the Options, alternatives or new courses of action; and
- W: Determining a Way forward in terms of actions to be taken.

Most participants of the executive coaching initiative reported extremely positive experiences and learning opportunities. They wholeheartedly recommended this approach to other colleagues who are committed to making changes and are receptive to frank discussions and feedback.

Looking Ahead

While it is still early to determine the impact of these initiatives on the overall productivity and morale of the Department, some positive results have nonetheless been achieved. Foremost, the management initiatives have raised awareness amongst both staff as well as those in leadership positions of the importance of the tangible as well as intangible aspects of culture along with how these aspects should be actively managed. This is essential in order to create an enabling work environment which is conducive to meeting the challenges ahead in an efficient and effective manner. Across the Department, "Management Matters" has become a mantra; at every quarterly Departmental meeting, there is a concerted effort to update staff members on the status of the various relevant initiatives thus continuously building greater awareness and accountability.

In addition, these initiatives and their results have been noted and appreciated by several of the IAEA's member states who have contributed both financially as well as through expertise toward their continuation and future evolution.

So far, most of the initiatives have been aimed at improving the leadership skills and competency at the individual level. Going forward, complementary initiatives addressing team performance at all levels of the Department will be undertaken. Such initiatives could take the form of team coaching that provides a structured context to both support and challenge a group to grow and increase its collective performance over time. It is a process that can lead to sustainable change and performance improvement at the group level in much the same way that one-to-one coaching influences such professional growth at the individual level.

Leadership development and culture change activities are not a one-off exercise. Rather they need to continuously adapt and evolve, anticipating and responding to the challenges faced by the organization. There is also a need to identify means for objectively assessing the impact of the various initiatives planned and implemented over time.

There is hope and expectation that continued internal efforts as well as support and continued extra-budgetary contributions from IAEA member states will allow for such initiatives to be sustained in the foreseeable future thereby contributing directly to the achievement of the challenging objectives and overall mission of the Department of Safeguards.

End Notes and References

1. De Raedemaecker, et al: '*Bringing out the Best in People*'; McKinsey Quarterly, January 2015.
2. Fesel, Mayol, and Srinivasan: *'Decoding Leadership: What really matters'*; McKinsey Quarterly, January 2015.
3. One significant quantity is the approximate amount of nuclear material for which the possibility of manufacturing a nuclear explosive device cannot be excluded.
4. IAEA website: https://www.iaea.org/safeguards/basics-of-iaea-safeguards/safeguards-facts-and-figures
5. Schein, Edgar: *Organizational Culture and Leadership*, 1992.
6. Van Vliet, V. (2013): Organizational culture model (Schein). http://www.toolshero.com/organizational-culture-model-schein.
7. How well a test measures what it is purported to measure.
8. The degree to which an assessment tool produces stable and consistent results.
9. According to the IAEA Administrative Manual, the primary purpose of the IAEA Staff Association is to safeguard the rights and promote the interests and welfare of all members of the IAEA's staff, and to ensure that working conditions are in accordance with the principles of the United Nations Charter, the Universal Declaration of Human Rights, the IAEA's Statute and the Staff Regulations and Rules.
10. Employee engagement is defined in modern management as the emotional commitment the employee has to the organization and its goals.
11. When a meeting, or part thereof, is held under the Chatham House Rule, participants are free to use the information received, but neither the identity nor the affiliation of the speaker(s), nor that of any other participant, may be revealed.
12. *The State of Human Capital 2012—False Summit: Why the Human Capital Function Still Has Far to Go*, a joint report from The Conference Board and McKinsey, October 2012.
13. Modernization of Safeguards Information Technology.
14. Refers to the general notion of implementing safeguards in a manner that considers a state's nuclear and nuclear-related activities and capabilities as a whole, within the scope of the State's safeguards agreement.

Engagement between the IAEA Operations Divisions and State Authorities on Safeguards Implementation

John Lepingwell, Teshome Bayou Temesgen, and Jose Araujo
IAEA Department of Safeguards, Division of Operations A, B, and C respectively

Introduction

The International Atomic Energy Agency (IAEA) Department of Safeguards cooperates with state and regional authorities responsible for safeguards implementation (SRAs) to implement safeguards. (While the acronym SRA applies to both state and regional authorities responsible for safeguards implementation, most of the cases reviewed in this paper apply to state authorities. The more generic term will still be used, however, unless the reference is to a state-specific issue.) Such cooperation is an obligation of the IAEA and the state pursuant to a comprehensive safeguards agreement (CSA). Cooperation is important in all aspects of carrying out safeguards, e.g., reporting nuclear material inventories, conducting verification activities in the field, responding to requests and notifications, and consulting on modifications to a safeguards approach. Concluding an additional protocol extends such cooperation to other activities, such as preparing and submitting declarations, and facilitating complementary access.

In addition to cooperation in safeguards implementation, the Department engages with states through training, advisory missions, outreach on the conclusion of safeguards agreements and protocols, and ongoing exchanges on technical safeguards developments.

This paper describes some of the challenges states face in implementing safeguards, and then reviews the broader aspects of engagement between the IAEA and SRAs, with a particular focus on the bilateral capacity building and cooperation efforts undertaken by the Divisions of Operations in the Department of Safeguards.

Common Challenges Facing State and Regional Authorities (SRAs)

The performance of state and regional authorities (SRAs) and the effectiveness of SSACs have a significant impact upon the effectiveness and efficiency of safeguards implementation. In 2014, in some states, SSACs had yet to be established, while in other states the IAEA had difficulty identifying a point of contact with whom to communicate on safeguards matters. Moreover, not all SRAs have the necessary authority, independence, resources, or technical capabilities to fully implement their obligations pursuant to safeguards agreements and additional protocols (AP), where applicable.

State authorities in some states often have to cope with competing regulatory priorities, funding constraints and difficulties with personnel recruiting, retention, and training. A state authority may also face challenges in collecting data and navigating the complexities of nuclear material accounting, reporting and additional protocol declarations (where applicable).

The main safeguards implementation difficulties encountered by the IAEA include: (i) delays in placement of new facilities under safeguards and late provision of design information; (ii) delayed feedback on proposed new measures or updated safeguards approaches; (iii) inability to use enhanced safeguards measures such as remote monitoring; (iv) delays in the submission of accountancy reports and AP declarations; (v) insufficient oversight by state authorities of nuclear material accounting and control systems at nuclear facilities and LOFs to ensure the required accuracy and precision of the data transmitted to the IAEA; and (vi) limiting the number of designated inspectors and not providing multiple entry visas valid for at least a year.

Particularly challenging for state authorities is the collection of information on nuclear fuel cycle related research and development not involving nuclear material (AP articles 2.a.(i) and 2.b.(i)). Obtaining this information often requires the state authority to liaise with a wide range of governmental and commercial organizations, which is a very different undertaking than nuclear material accountancy and the conduct of inspections.

Finally, each SRA has to manage the interactions and interests of operators, companies, research institutes, and government agencies, and coordinate the interface with the IAEA. This requires experience, knowledge of safeguards and management competence to be sustained over time.

As noted in Kinney 2015, experience has shown that many states that have concluded a small quantities protocol (SQP) to their CSA (hereafter referred to as SQP states) also face a number of common challenges. Among these are high staff turnover in the state authority; lack of familiarity with safeguards or the IAEA (many do not have missions in Vienna); and infrequent communications with the IAEA on safeguards matters. For states adopting a revised SQP or concluding an AP, these challenges can significantly affect the ability of the state authority to fulfill obligations for reporting and facilitating verification activities. The state needs the regulatory framework, processes, and mechanisms to collect and provide the required information to the IAEA, which requires an understanding of the obligations.

Establishing the necessary legislative and regulatory framework and the organizational capacity to implement it is a first step. For states without such a framework and with little or no experience with safeguards, it is often difficult to know how to start. The IAEA's Office of Legal Affairs (OLA) works closely with states, providing advice and assistance in drafting comprehensive nuclear legislation and regulations that address not only safeguards, but also safety and security. This is an essential step towards building an effective, independent state authority.

Responsibility for nuclear safeguards may be vested in existing state authorities with responsibility for the security and safety of radioactive materials or placed in technical organizations responsible for liaising with the IAEA on technical cooperation projects. In states with very limited regulatory infrastructures, responsibility may be temporarily placed in a law enforcement agency, environmental agency, or in the ministry of foreign affairs. An important first step, irrespective of where the responsibilities lie, is to initiate communication with the IAEA Department of Safeguards.

Just thirty days after the end of the month in which a state adopts the revised text SQP, the initial nuclear material inventory report is to be submitted. If the state is well prepared and has an effective SSAC, this short timeframe may not pose a challenge. In other cases, collecting the information and preparing the initial report may take considerable time, even if there is little or no nuclear material to report.

The SRA first needs to collect the required information, process it and submit it to the IAEA. If a state already has a system to track radioactive sources, then this may provide much of the required information (not because radioactive sources are reported as inventory, but because the most common use of nuclear material in SQP states is in depleted uranium shielding for radioactive sources). The state then needs to keep track of its nuclear material inventory over time, collecting and reporting information on an ongoing basis on the movement of nuclear material within the state and across its borders. Any changes in the inventory are to be reported to the IAEA on an annual basis or as the changes occur.

Reflecting these challenges, in 2014, thirteen (out of fifty-three) states with a revised SQP in force had yet to submit an initial nuclear material inventory report. The IAEA has tried to facilitate the reporting process by developing simplified nuclear material reporting forms as well as by providing training and workshops at the national, regional, and global level. Even with these steps, however, the process of implementing safeguards is a demanding one for many states. The IAEA's recent focus has been on providing training to states in the process of revising their SQP or bringing an AP into force, with a special emphasis on supporting the establishment of the SRA.

The AP poses additional, but related, challenges. In many cases, a state with an SQP may have very little or nothing to declare under its AP. However, the state needs to confirm what it does *not* have, as well as to keep track of what it *does* have. This requires an understanding of the various materials, activities and equipment specified in the AP and its annexes and a system to monitor such activities in the state over time.

The first comprehensive set of AP declarations has to be submitted to the IAEA within 180 days from the date the AP enters into force. These declarations must then be updated annually and AP declarations on relevant exports must be submitted on a quarterly basis. For the state to confidently submit a complete and correct AP declaration, it requires an adequate information collection and evaluation process. Again, training on the requirements of the AP is highly recommended in advance of entry into force. Even so, the state authority may have questions for the IAEA during the 180 day period before the initial declarations are to be submitted. Such working level communication, e.g., by email, between the state authority and the IAEA Division of Operations, is very helpful during such transition phases.

Engagement between the IAEA and SRAs

To meet the wide range of challenges encountered by states in implementing safeguards, the IAEA undertakes a number of activities targeted at meeting the specific needs of states. These range from providing advice and assistance in conjunction with in-field activities, to training, outreach, technical implementation meetings, and liaison committees. Some engagement is targeted specifically toward states with SQPs.

General Safeguards Outreach and Training

The IAEA conducts a range of safeguards outreach and training programs. Most outreach activities focus on encouraging states to conclude an AP or to modify an SQP; these are organized by the Director General's Office of Coordination (DGOC). After a state has decided to take such action, the emphasis shifts to training on specific issues regarding safeguards implementation.

The Training Section of the Department of Safeguards working together with member states and other sections and divisions of the Department of Safeguards, as well as DGOC and OLA, organizes a variety of training activities for states. In some cases this training may be narrowly focused on a specific topic (e.g., nuclear material accounting issues in a particular state) and in other cases it may involve broad safeguards training for more than a dozen states. The IAEA has very limited regular budget funding for SSAC training so these activities are primarily funded through extra-budgetary funding and/or in conjunction with training activities sponsored by member states.

In order to make the most efficient use of limited IAEA funds and to encourage interaction among safeguards practitioners, training is often conducted on a regional basis. Regional training facilitates the exchange of experience between safeguards practitioners and formation of peer networks. In some cases, these networks are formalized, such as the Asia Pacific Safeguards Network (APSN).

For training to be most effective, whether held regionally or in Vienna, the training needs to be directed to the right people. Sometimes higher level personnel are nominated to attend IAEA training rather than personnel directly involved in implementation of safeguards. While this is advantageous when the state is trying to gain an initial understanding of its safeguards responsibilities, the emphasis should eventually shift to training those personnel directly involved in safeguards implementation, possibly including facility or locations outside facilities (LOF) operators. Once individuals are trained, it is important that they be retained. Some states request national training to allow several staff to attend. Such trainings are relatively rare due to the cost involved, but those that are held are often carried out in conjunction with inspections.

Missions, Visits, and Meetings

The Department of Safeguards holds a variety of meetings with SRAs, both in Vienna and in the state; some are high level, formal meetings and others are working level exchanges. Meetings are often held with delegates on the margins of the annual IAEA General Conference. Operations Divisions will arrange meetings with their counterparts attending IAEA training courses, seminars or workshops held in Vienna. Meetings often take place in conjunction with verification activities carried out in the states.

Safeguards implementation visits are sometimes arranged for Operations Divisions to meet with state authorities in states with limited nuclear material and activities, where access infrequently takes place (e.g., states with original SQPs). During such visits, presentations on IAEA safeguards are provided, any safeguards issues are discussed (such as modification of an SQP, or response to IAEA communication) and action plans may be prepared to identify follow-up activities. During the last five years (2010 to 2014) the Department of Safeguards carried out these visits in more than twenty states. The obligations of a state under both a revised SQP and AP were explained, as was the obligation to create and maintain an independent and functional SSAC. Hands-on assistance was provided in understanding how to prepare a nuclear material inventory report, collect information and prepare AP declarations. In some states, locations where nuclear material is customarily used (e.g., hospitals, industries, central storages) were visited and equipment was identified that contained nuclear material.

These visits helped the state authorities better understand and fulfill their safeguards obligations and to provide the IAEA with outstanding declarations and/or initial nuclear inventory reports as applicable. During the visits, the importance of establishing and maintaining an independent SSAC was reinforced. To sustain communication with the IAEA, the importance of establishing points of contacts at the different levels based on institutions rather than individuals was also highlighted. These visits take time and commitment of both the IAEA and the states, but in many cases, the outcomes are quite positive.

Cooperation mechanisms are sometimes formalized in states, by setting up committees or working groups. For example, the IAEA and EURATOM have organized Liaison Committees to strengthen their cooperation in safeguards implementation. The cooperation is put into practice through the development of 'Partnership Approaches,' which address a variety of practical implementation areas, such as development of equipment and conduct of activities in the field. Joint training of staff from both organizations is also addressed, including identifying common needs for training, conducting common training courses and exchanging relevant technical information. The yearly training programs of both organizations are also shared. During the last few years, joint trainings were provided on Partnership Approaches, teamwork and communication; safeguarding specific types of facilities; instruments used during inspections; and the complementary access activities.

To help states build their capacity to comply with their safeguards obligations, in the last five years (2010 to 2014) the IAEA conducted seven IAEA SSAC Advisory Service (ISSAS) missions in Kazakhstan, Mexico, Moldova, Tajikistan, Kyrgyzstan, the United Arab Emirates, and Uzbekistan. The service provides states, at their request, with advice and recommendations on the establishment and strengthening of such state systems. The comprehensive nature of the ISSAS limits the number of missions that can be conducted in a year, therefore less comprehensive but effective engagement with states has also been conducted.

Regional organizations also provide an opportunity not only for IAEA engagement with states but also for sharing of safeguards experience and knowledge among states. The APSN mentioned earlier, for example, has been especially active in this regard. In addition to a regular annual meeting of states in the Asia Pacific region, the APSN in 2015 hosted its first multilateral training workshop in Indonesia with the support of the United States. This kind of initiative supports and enhances the IAEA's engagement with states and is a welcome development.

Some states are also taking the initiative to develop regional centers for training in safeguards, security, and safety. Japan and the Republic of Korea have both developed safeguards training workshops which are conducted jointly with the IAEA and with participants from a wide range of states from Asia and other regions. The Brazilian-Argentina regional authority, ABACC, also conducts training for its safeguards inspectors in coordination with the IAEA on a regular basis.

The IAEA also reaches out to states and the international safeguards community through its symposia and other activities. In October 2014 the IAEA held its twelfth Symposium on International Safeguards in Vienna with the objectives of fostering dialogue, exchanging information and promoting cooperation between the Secretariat, member states, the nuclear industry and members of the broader safeguards and nuclear nonproliferation community. More than 600 participants took part in the symposium and more than 300 papers were presented.

Finally, the IAEA has been engaging with the member states through technical meetings held in Vienna. In recent years, these have tended to focus on specific issues such as technical background information on reports to the Board, or on safeguards implementation at the state level. In 2015, three technical meetings on safeguards matters have been held, one of which focused on safeguards implementation in states with SQPs and the resources and assistance offered by the IAEA related to safeguards.

IAEA Publications and Website

Over the past several years the IAEA has significantly expanded the range of safeguards guidance documents available for states. In December 2014, an updated version of the *Guidance for States Implementing Comprehensive Safeguards Agreements and Additional Protocols* (IAEA Services Series 21) was published and is now being translated into Spanish and Russian. In addition, the first of four guides on safeguards implementation practices was published in December 2014 titled, *Safeguards Implementation Practices Guide on Facilitating IAEA Verification Activities* (IAEA Services Series 30). In February 2015, the *Safeguards Implementation Practices Guide on Establishing and Maintaining State Safeguards Infrastructure* (IAEA Services Series 31) was published. Two more Safeguards Implementation Practices (SIP) guides are under development for publication in 2016, addressing 1) Providing Information to the IAEA; and (2) Collaborative Approaches to Safeguards Implementation.

All safeguards guidance, as well as forms, templates, instructions, and information about training and advisory services are available to states at the assistance for states (www.iaea.org/safeguards) web page. This site is continuously improved and expanded to ensure the most current guidance and tools are available to states. The safeguards-by-design series of guidance is available at this site, as well as references such as the International Target Values and the safeguards glossary. When the next version of Protocol Reporter software is released, it will also be available on the "software and tools" tab on this page.

Targeted Engagement with SQP states

Some training courses are organized specifically for representatives from states with SQPs. Although the IAEA's training resources are very limited, some member states have provided substantial training and assistance targeted at states with SQPs, through bilateral training programs. The IAEA focuses its efforts on SQP-specific international and regional training courses and training for SQP states that are preparing to adopt the revised text of the SQP or to bring an AP into force.

For example, the IAEA organized an international SSAC course for states with SQPs in the United States in November 2014. The course brought together more than twenty-five participants from SQP states around the world and provided intensive training on both the revised SQP and the AP. A particularly important aspect of the workshop was the opportunity for representatives of different state authorities to exchange their experience and knowledge. The workshop was funded by the U.S. Department of Energy and presentations were made by experts from the IAEA as well as the U.S. International Nuclear Safeguards and Engagement Program (INSEP). Many other states, such as Japan, Republic of Korea, and Finland, host training courses in cooperation with the IAEA.

Over the last five years, the IAEA has organized several outreach programs and held consultations with member states encouraging them to conclude APs and to amend their SQPs. In the Asia-Pacific region alone, outreach events were held in Singapore (2011) for the Southeast and South Asian states; in Fiji (2012) for the Pacific region. In addition, targeted assistance was provided to a number of individual states, including Brunei Darussalam (June 2014); Laos (August 2013); and Myanmar (August 2013, December 2014). Consultations on the conclusion of safeguards agreements and additional protocols are held each year with representatives from various states in Geneva, New York, and Vienna.

To assist SQP states in building capacity for implementing their safeguards obligations, the IAEA published the *Safeguards Implementation Guide for States with Small Quantities Protocols (IAEA Services Series 22)* in English in 2013, and in 2014, published it in French and Spanish and sent copies to all states with SQPs.

The IAEA has also developed the AP Protocol Reporter software to help states track and submit AP declarations, and it is provided to member states free of charge. However, using software can be difficult when it is only needed a few times per year. A new version of the Protocol Reporter software is expected to be deployed in 2016 and it should address many of the usability problems that have been reported.

The IAEA continues to encourage states to modify SQPs based on the original text, and to bring APs into force. The establishment of capable, effective state authorities and SSACs in SQP states is essential to effective safeguards.

The Way Forward

Engagement is an ongoing process. It must evolve to meet the needs of the states while at the same time making the most efficient use of IAEA and state resources. Based on recent experience, a number of areas offer possibilities for improved engagement to increase the effectiveness and efficiency of safeguards.

The IAEA's continued development of tools, forms and instructional material could simplify the process of nuclear material and AP reporting, especially for SQP states. Initiatives such as MOSAIC (the IAEA's modernization of its IT infrastructure) project to develop a state Declarations Portal that would allow states to upload their nuclear material reports and the new version of Protocol Reporter are important developments toward this end.

The IAEA has significantly increased the number of published guides and other assistance for states through the IAEA's website. These collections could be expanded over time taking into account feedback from member states. A further step in this direction could be the production of online tutorials on specific reporting and declaration topics for use in training in member states.

The IAEA's "one-house approach" for coordinating its work in safeguards, nuclear security, and safety (among other areas) is beneficial to those state authorities that address these activities in one office. This is often the case in states with limited nuclear activities, where increased awareness of the potential synergies in these fields could boost their efficiency and strengthen oversight efforts.

Regional networks that encourage peer-to-peer training and sharing of safeguards experience, and training centers established in member states are useful mechanisms for engagement. Coordination with the IAEA can help to reduce duplication of effort, ensure training materials are up-to-date, and facilitate direct IAEA participation in events as appropriate.

The timing of training has an impact on its effectiveness. Training will be important during the period just before and after a revised text SQP or AP enters into force. States need training on the details of nuclear material accounting/reporting and AP declarations when undertaking the initial practical steps towards implementation.

Conclusions

International legal obligations undertaken by states need to be incorporated into the national legislative framework and oversight mechanisms. Limited resources are a global reality, but a modest investment in establishing a capable state safeguards authority and a functioning SSAC pays significant dividends. The state can have increased confidence in its control over its nuclear material inventory and its nuclear activities and trade, and a mechanism for effective and sustained cooperation with the IAEA in safeguards implementation. Making effective use of IAEA training and engagement will produce the best results when states clearly identify and assign safeguards responsibilities and consistently train and support the key individuals.

Technical Outreach on Nuclear Material Accounting Reporting – Examples of Trilateral Engagement Among the IAEA, State, and Operator

R. Kaulich, E. Gyane, C. Norman, and A. Rialhe
International Atomic Energy Agency, Vienna, Austria

Introduction

IAEA safeguards implementation involves the verification of information submitted to the International Atomic Energy Agency (IAEA) by states regarding their nuclear material and activities. Paragraph 29 of INFCIRC/153 (Corr.) provides for the use of nuclear material accountancy as a safeguards measure of fundamental importance, with containment and surveillance as important complementary measures.

Nuclear Material Accountancy

Nuclear material accountancy within the framework of IAEA safeguards begins with the nuclear material accounting activities by the facility operator, which accounts for nuclear material within material balance areas (MBA); periodically determine the quantities of nuclear material present within each MBA through the taking of the physical inventory and tracking of any transfers into and out of the MBA; and reports any inventory changes and inventories to the state (or regional) authority responsible for safeguards (SRA).

The SRA verifies the operator's performance and ensures that agreed procedures and arrangements are adhered to. Based on the information received from the operators, the SRA prepares the respective nuclear material accounting (NMA) reports – inventory change reports (ICRs), physical inventory listings (PILs) and material balance reports (MBRs) – for transmission to the IAEA. It also provides for IAEA inspector access and coordinates arrangements as necessary to facilitate the IAEA's verification activities.

The IAEA independently verifies nuclear material accounting information in facility records and NMA reports and conducts other activities as provided for in the safeguards agreement. The IAEA also takes into account the capabilities of the state system of accounting for and control of nuclear material (SSAC) and provides statements to the SRA on the IAEA's verification activities.

In practice, IAEA inspectors are the primary interface between the Department of Safeguards and the state authorities and facility operators.

Section for Declared Information Analysis

The Section for Declared Information Analysis (ISD) in the Division of Information Management of the IAEA's Department of Safeguards is the Department's clearinghouse for all state declared information. It thus plays a key role in handling state declared information, the information submitted by states under their respective safeguards agreements and voluntary undertakings (INFCIRC/153-type agreements, INFCIRC/66-type agreements, Voluntary Offer Agreements, additional protocols, Voluntary Reporting Scheme information, and neptunium and americium information).

ISD receives data by encrypted email or physical transfer (e.g., by digital media or, in rare cases, on paper). It then processes all reports and declarations and carries out quality control to check the formatting and correctness of the information. ISD maintains the data in different databases and assures the correctness and reliability of all data in the databases. It evaluates the state declarations and conducts a consistency analysis of the information. It also provides information services (reports, summaries, analyses) to the Divisions of Operations in the Department of Safeguards. By evaluating the state reports and declarations, ISD contributes to the state evaluation process and plays an essential role in the drawing of safeguards conclusions.

On an annual basis, the IAEA currently receives some 960,000 declarations and report entries provided by the states. The volume of safeguards-relevant information has continued to rise over the past decade and this trend is expected to continue in the future. To streamline and prioritize the associated workflows and processes, new tools and methodologies are being investigated by ISD to improve the quality of the state declared information.

Cooperation between the IAEA and States in Safeguards Implementation

The cooperation between the states and the IAEA, as a means of enhancing the effectiveness of the SSAC, may be seen as a cornerstone for the efficient implementation of safeguards. It is in the best interest of all stakeholders that this cooperation is as good as possible and improved if needed. Cooperation also needs to include operators of facilities and locations outside facilities (LOF), since the SRAs are highly dependent on receiving all facility information in a timely manner and of the highest quality.

The SRA is the primary working-level interface between the state and the IAEA. Its functions can be many-fold but SRAs should facilitate the verification activities of the IAEA, ensure a well-functioning SSAC and submit information to the IAEA. Some key good practices of SRAs include:

- Training SRA staff and facility and LOF operators to ensure awareness of and compliance with reporting obligations;
- Outreach to industrial and research entities to ensure that all necessary information is provided to the SRA (e.g., with regard to declarations under an additional protocol); and
- Proactively communicating with the IAEA on safeguards matters.[1]

The recently released IAEA publication *Safeguards Implementation Practices Guide on Establishing and Maintaining State Safeguards Infrastructure*[2] was designed especially to meet states' needs is expected to be useful in upcoming outreach activities by giving advice and providing practical examples of states' experiences with safeguards implementation.

Past experience has shown that training and development of safeguards expertise in states is a continuous need, particularly due to turnover of staff at facilities and SRAs, as well as the adoption of new technologies and methods. This may be complicated by a lack of training or reference materials on safeguards-related subjects, insufficient financial or technical resources, incomplete national legislation, or an aging workforce. All of these factors and others may have an impact on cooperation with the IAEA. It is therefore in the interest of all stakeholders to address such factors as a means of improving cooperation.

The number of nuclear material and facilities and quantities of nuclear material under safeguards is rising. In a resource constrained environment, the IAEA will therefore have to look for ways to improve its efficiency and effectiveness by optimizing its internal processes, using modern technology in a smarter way and improving its cooperation with SRAs in safeguards implementation.[3]

The following areas still leave room for improvement:

- The timeliness, accuracy, and completeness of state declarations;
- The quality of the operators' measurement and accounting procedures;
- SSACs that are not fully established; and
- SRAs that lack the necessary authority, independence, resources, or technical capabilities to fully implement the requirements of their safeguards agreements and additional protocols.

IAEA invests resources to address these areas through training SRAs and operators, and providing targeted assistance.

IAEA Training

The IAEA provides the following support to states in order to improve cooperation, in the area of safeguards and beyond:

- IAEA SSAC Advisory Services (ISSAS) missions;[4]
- Integrated Nuclear Infrastructure Review (INIR) missions;
- Training courses (regional/interregional/international level);
- E-learning modules (developed in 2014) explaining the IAEA Milestone Approach;[5]
- Technical documents (TECDOCs);[6]
- Guidance documents (IAEA Services Series 11, 15, 21, 22, 30 and 31);
- Other outreach (e.g., technical meetings, annual safeguards implementation meetings, etc.);
- Safeguards symposia (forum to exchange views between the IAEA and SRAs, and members of the broader safeguards and nuclear non-proliferation community);
- IAEA conferences (those addressing the safeguards needs in connection with building a competent workforce in member states).[7]

Outreach and training by the IAEA Safeguards Training Section play an essential role in ensuring that nuclear professionals in states are well prepared to carry out functions of the SSAC, both at the facility and at the state level.[5] They complement the focused training provided by ISD and the Nuclear Fuel Cycle Analysis Section (IFC), both in the Division of Safeguards Information Management (SGIM), in cooperation with the Safeguards Divisions of Operations (SGOs).

Training—Experiences Gained

In order to further enhance these supporting activities for SRAs, the IAEA has engaged in technical outreach activities focused on nuclear material accounting for SRAs and operators. These outreach activities are mainly performed by SGIM[8] in cooperation with the country officers[9] and other staff from the Divisions of Operations responsible for the respective state. In some cases, the Safeguards Training Section assists with the outreach activities.

As detailed above, SGIM is not only responsible for receiving and processing nuclear material accounting reports but it handles all state declared information submitted under states' safeguards agreements and voluntary undertakings. For technical outreach activities, SGIM usually prepares a number of suitable practical exercises for workshops based on realistic scenarios and using actual NMA data from the respective state. Thorough preparation is a prerequisite for this type of interactive training, which provides the participants with the opportunity to practically apply their theoretical knowledge, ask questions and create solutions for real work scenarios.

This training approach is best described by the following adjectives:

- accurate
- timely
- problem/solution-targeted
- country-specific

These outreach activities aim at improving the quality of NMA reports, thereby decreasing the IAEA's workload. It is expected that this type of focused training will further improve cooperation and facilitate safeguards implementation by forming informal bridges between the stakeholders, thus creating competent partners in case problems arise.

Outreach activities are organized jointly by the IAEA and the respective state. While the IAEA is responsible for the preparation of the course material, the state provides the training premises and if possible access to a nuclear facility in the state. SGIM is tasked by the Operations Divisions responsible for the specific state to prepare the training materials, which consist of presentations, practical exercises and supporting documents. Participants may be facility operators or SRA staff. These courses are specifically tailored to meet the respective state's training needs. The use of real national NMA data during the workshops provides the participants with a better understanding of the issues presented. SGIM first provides an overview on the safeguards agreements in place with the respective state and then presents known problem areas in the workshop examples. This way the participants get an overview of their state's responsibilities with regard to nuclear material accounting and get an opportunity to practice in corresponding workshops.

Usually course participants are provided with the latest versions of the Quality Control Verification Software (QCVS) and the Protocol Reporter software. The development of the QCVS was funded by the United States Support Program and the software was developed by the company AWST and the IAEA. The software was developed to assist states in the preparation of NMA reports and their transcription into .txt files, which is currently the only electronic format acceptable for fixed format NMA reports. The Protocol Reporter was developed by the IAEA to assist states in the creation and preparation of declarations pursuant to articles 2 and 3 of an additional protocol. During the course ISD helps with the installation of the software tools and explains their functions and use to the respective SRA staff.

In order to decrease manual workload for both the state and the IAEA, SRAs are encouraged to send machine-readable data to the IAEA. Outreach training provides a perfect opportunity to give detailed advice on all IT-related matters with respect to the electronic submission of NMA data.

The use of modern technology looks easy at first sight but the transition from hard-copy to electronic declarations sometimes presents significant difficulties for the SRAs.

Experience has shown that the possibility to train SRA personnel together with facility or LOF operators opens up a discussion forum for both parties on different topics. Facility operators usually have a very good knowledge of their responsibilities but also of their rights. As became obvious in some of the latest outreach activities, the majority of LOF operators were not aware of their reporting responsibilities towards the SRAs. From their point of view, the relevant licensing systems in place (which often do not include any safeguards-related provisions) were perceived to be sufficient in terms of complying with their obligations towards the SRAs.

In the rare cases where no legal system, including provisions related to safeguards, has been established by a state, there exists a real problem with respect to safeguards implementation as NMA reports are either not submitted at all or not in a timely manner. SGIM has therefore tried to engage operators by educating them on the consequences that this lack of information provision poses to their state. In a specific case, SRA personnel were advised to reach out to operators on a regular basis in order to receive the necessary information on time. Although this can be only an interim solution until official legislation is in force, it may be a first step towards the establishment of a national legal framework.

In one of the most recent outreach activities, the Department held workshops that specifically addressed the problems encountered in reporting for a specific MBA. Several presentations were delivered and in a follow-on workshop the participants were shown the particular NMA reports previously submitted to the IAEA. The problems which had arisen from incorrect, late or missing reports were highlighted and solutions for these problems were worked out together with the participants.

Experience has shown that when SRA staff have the opportunity to personally discuss NMA reports with the IAEA staff who work with these types of reports on a daily basis, valuable information can be exchanged that very often leads to a better understanding and enables reporting to be optimized.

The atmosphere in this kind of outreach is open and collegial and provides the framework for creating and strengthening working level relations among peers at the IAEA and at the SRAs and facilities. Working level interactions can facilitate understanding and comprehension communicating clearly and giving examples that are easy to understand. The personal contacts created through such outreach activities provide a valuable basis for increased information exchange and communication when problems regarding NMA reports arise. Contacts with operators are also helpful, but these interactions are facilitated through the SRA, who is the direct counterpart with regard to the submission of NMA reports. Therefore, it is important to encourage operators to cooperate closely with their SRA.

Very often, the SRAs do not invite LOF operators to participate in all of the workshops provided by the IAEA because of the confidentiality of NMA data. Therefore, the presentations given by the IAEA can only be seen as a first step towards proper education of a state's safeguards workforce. These outreach activities could be useful for the LOFs and SRAs can play an important role in sharing the materials with them. Some common challenges faced by many of the SRAs with regard to NMA reporting can negatively influence the flow of information, such as:

- Aging workforces (key personnel retiring without adequately trained successors);
- No knowledge management processes in place (one person show);
- Unclear national and/or legal competencies (no law and/or law enforcement); and
- Limited number of staff responsible for safeguards implementation (financial restrictions).

It is anticipated that with an enhanced understanding of rights and responsibilities of SRA personnel and facility/LOF operators, the cooperation related to safeguards in other fields will profit as well (e.g., incorporation of safeguards features into the design of new facilities).

Conclusion

Over the past few years SGIM, upon request by and in cooperation with the Divisions of Operations of the Department of Safeguards, has conducted several trilateral outreach activities to various countries in order to strengthen the capabilities of their SRAs; educate their personnel specifically on NMA reporting and AP declarations; provide relevant software; solve outstanding reporting issues; and assist in the improvement of the operators' accounting and measurement system.

Since then, a number of countries have successfully transitioned from hardcopy to electronic submission of NMA reports to the great benefit of the IAEA. With the input from relevant SRA staff, SGIM was able to solve many problems related to analyzing NMA reports. Advice was given on how to reach out to LOF operators in several countries and workshops on additional protocol declarations were conducted in states with an AP in force. SGIM has not only focused on providing knowledge to the SRAs but also on establishing valuable contacts for the future to ensure a smooth and timely submission of correct and complete NMA reports.

The practical cooperation between the SRA, the facility and LOF operators, and the IAEA is one of the cornerstones to successful implementation of IAEA safeguards. The day-to-day implementation works best when it is conducted as a cooperative effort among SRAs, operators and the IAEA, with all parties sharing a common understanding and seeking to achieve a successful outcome. One way to foster a proactive partnership is to approach state authorities that are in need of guidance and support them by providing tailored training for the SRAs and the operators, thus building informal bridges and increasing the support of IAEA implementation activities. These outreach activities are targeted to the audience, can be provided in a timely manner and create a climate of confidence and cooperation to the mutual benefit of states and the IAEA.

End Notes

1. The provisions of the voluntary offer agreements concluded by nuclear weapon states or the item specific safeguards agreements concluded by the states outside the NPT are not explicitly covered by this paper.
2. Fundamentals and Good Practices of Safeguards Regulatory Authorities. A paper by the Asia-Pacific Safeguards Network (APSN). Communication dated December 14, 2012, received from the Australian Government. INFCIRC/845. Date January 8, 2013.
3. Safeguards Implementation Practices Guide on Establishing and Maintaining State Safeguards Infrastructure. IAEA Services Series No. 31, Vienna, February 2015.
4. Activities of the International Atomic Energy Agency relevant to article III of the Treaty on the Nonproliferation of Nuclear Weapons, Background paper prepared by the Secretariat of the International Atomic Energy Agency, 2015 Review Conference of the Parties to the Treaty on the Non-Proliferation of Nuclear Weapons, New York, 27 April-22 May 2015, https://www.iaea.org/newscenter/focus/npt (accessed May 5, 2015).
5. A. Braunegger-Gülich, V. Cisar, J.-M. Crété, R. Stevens. 2014. IAEA support for building-up a highly skilled workforce necessary for an effective State System of Accounting for and Control of Nuclear Material; *Proceedings of the 55th INMM Annual Meeting*.
6. Milestones in the Development of a National Infrastructure for Nuclear Power, IAEA Nuclear Energy Series No. NG-G3.1 (2007)
7. E.g. IAEA-TECDOC-1254, IAEA, November 2001. Training the staff of the regulatory body for nuclear facilities: A competency framework
8. IAEA. 2012. Proceedings Series. Human Resource Development for Introducing and Expanding Nuclear Power Programmes, Summary of an International Conference, Abu Dhabi, United Arab Emirates March 14-18, 2010.
9. SGIM-IFC provides special training courses on aspects of accounting related to measurement, physical inventory taking and material balance evaluation methods in States holding bulk handling facilities.
10. Country officers are inspectors working in Divisions of Operations of the Department of Safeguards. They have been assigned the direct responsibility for dealing with day-to-day safeguards matters in related States.

Safeguards Implementation for States with Small Quantities Protocols

John Kinney
Department of Safeguards, International Atomic Energy,Vienna, Austria

Abstract

What is a small quantities protocol (SQP)? What is an SQP state? Why have safeguards for SQP states come to such prominence? The origin of and the reasoning behind SQPs to comprehensive safeguards agreements are explored and the circumstances that led to the need to modify the model SQP text are elaborated upon. Also addressed is the impact upon safeguards implementation for such states since the introduction of the modified SQP text. Suggestions are made as to efficiencies which could be achieved in respect of safeguards for such SQP states.

Introduction

It is more than forty years since the Board of Governors of the International Atomic Energy Agency (IAEA) established the Safeguards Committee (1970), or Committee 22, to draw up the structure and contents of safeguards agreements between states and the Agency required in connection with the Treaty on the Nonproliferation of Nuclear Weapons (the NPT).[1] As such, almost everyone who was involved in that process has long since retired.

It is hardly surprising that the origins of the small quantities protocol (SQP) to a comprehensive safeguards aggrement (CSA) and its purpose have faded into obscurity. This paper attempts to redress that situation and to elaborate on why the IAEA considered it necessary to revisit the SQP and to modify it.

The paper also looks at the implementation of safeguards under safeguards agreements with SQPs and explores where efficiencies can be introduced.

The Origin of the SQP

In February and March 1971, Committee 22 presented its formulation for the content and structure of NPT safeguards agreements, which became INFCIRC/153 (Corr),[2] but made no mention of exceptions to the provisions of such safeguards agreements.

At the board meeting in February 1972, three draft safeguards agreements with protocols holding in abeyance the implementation of most of Part II of the agreements (i.e., for Ireland, New Zealand, and Malaysia), were presented for approval. In connection with each of these safeguards agreements, the official record noted that the board took the action recommended (which was to approve the safeguards agreement with the IAEA) without any record of further discussion. This seems odd given that the foreword to the text of Ireland's agreement and protocols stated that comments on the protocols would be useful. In 2003, the Secretariat, in its review of the policy surrounding the model SQP, was unable to trace any record of negotiation of these three SQPs.

In the document submitting the draft Safeguards Agreement for Ireland for approval, the preamble also stated the following: "…the Irish authorities have informed the Secretariat that Ireland only has at present, in peaceful nuclear activities within its territory or under its jurisdiction or control anywhere, nuclear material in quantities below the limits stated in Article 36 of the agreement, and that this material is not in a facility." On that basis, the Secretariat of the IAEA and Ireland agreed on the protocol that would "reduce to a minimum the implementation of safeguards procedures under Part II of the agreement."

While it is true that Ireland did not have nuclear material subject to the Agreement in a facility as defined in Article 97.J of the Agreement, it did have nuclear material in substantial amounts in a sub-critical assembly[4] (a nuclear activity but not a nuclear facility), which constituted a "material balance area outside facilities," for which information would otherwise have had to be supplied under Article 48 of the Agreement. However, that provision was held in the abeyance by Protocol Number I of the Agreement. At the same time, New Zealand also had nuclear material in a sub-critical assembly.[5]

The same type of protocol was approved for a number of states until 1973 when, in the absence of any board discussion, it was recognized by one governor that the protocol had become, de facto, a standard for member states having no notable nuclear activities requiring the application of safeguards. This Governor proposed that the Secretariat publish a standard text for NPT agreements and simply inform the board of any deviations from that standard. In response, the Secretariat published GOV/INF/276,[3] which set out the standard text for comprehensive NPT safeguards agreement as Annex A to that GOV/INF, but more pertinently, the standard text for SQPs, which was attached as Annex B.

The Obligations and Weaknesses of the SQP

Under all CSAs, the IAEA has the right and obligation to verify that all nuclear material required to be safeguarded is in fact placed under safeguards, in accordance with the terms of the agreement. However, SQPs based on the original model hold in abeyance, or suspend, most of the provisions of Part II of the safeguards agreement, including those governing inspections, if the state met the eligibility requirements, i.e., it has nuclear material in amounts less than the limits specified in the agreement and has no nuclear material in a facility. The SQP did not obviate the requirements to establish a state system of accounting for and control of nuclear material or to report imports and exports of nuclear material.

To enable the timely (undefined) conclusion of Subsidiary Arrangements to its CSA, the SQP state was required to notify the IAEA sufficiently in advance of exceeding the limits of nuclear material or six months before the introduction of nuclear material into a facility, whichever occurred first.

Having an SQP allowed the state to have an existing nuclear facility but not provide the IAEA with design information so long as there was no nuclear material in the facility. After the discovery and dismantling of Iraq's clandestine nuclear weapons programme, the IAEA's efforts to strengthen the safeguards system by requiring states to provide design information at an early stage were negated in CSAs with such SQPs by virtue of its provisions.

The major failing of the original text SQP, in the Secretariat's view, was that the IAEA was unable to verify that a state met or continued to meet the eligibility criteria. In the absence of reports on nuclear material from an SQP state, the expectation that the IAEA would ensure that all nuclear material in peaceful nuclear activities had been declared and satisfy itself that the declarations were complete could not be met.

For an SQP state without an additional protocol[4] in force, the Department of Safeguards recognized the weakness in drawing the conclusion that declared nuclear material remained in peaceful nuclear activities when there had patently been no such declaration for fifty-eight of the seventy-one states at that time with operative SQPs. The Safeguards Implementation Report (SIR) for 2003 elaborated on the issue with the caution that: "…for a state in which an SQP is implemented but which does not have an additional protocol in force, the Agency has only very limited means to evaluate any potential nuclear activities in the state which might need to be declared to the Agency, or to confirm that the state meets or continues to meet the conditions required for having an operative SQP."

The Secretariat brought to the board's attention the shortcomings of SQPs and proposed possible solutions in a report by the Director General (DG) dated May 13, 2005. This action, however, was not taken in isolation—consultations with interested states took place between February and May 2005 on the basis of a Secretariat "Non-Paper" that drew member states' attention to the need to strengthen safeguards in respect of SQPs.

The DG's report suggested two possible solutions:

- The board would not approve any further CSAs with SQPs and existing SQPs would be rescinded; or
- If SQPs were to continue to be accepted, the text would be modified to make an SQP unavailable to a state with a planned or existing (nuclear) facility, to make provision of an initial report on nuclear material a requirement, to require the early provision of design information, and importantly, to make provision for IAEA inspections.

The board was invited to provide guidance to the Secretariat on how it wished to proceed in addressing the SQP issues. At the September 2005 Board meeting, the board chose to retain the acceptance of SQPs, but decided that it would, in future, approve only those SQPs which were modified as per the Secretariat's recommendation in the second option reflected above. The Board instructed the DG to effect that change in existing SQPs through an exchange of letters with each state—such exchanges of letters started soon thereafter.

The Secretariat indicated in its report to the Board that it did not foresee regular verification in states with modified SQPs and that there would be no measurable increase in safeguards costs to the IAEA. In addition, it noted that there would be little additional cost for states that revised or rescinded their SQPs, provided that the state had a mechanism in place to monitor its nuclear and other radioactive material. The board took note of that information.

Safeguards Implementation under the Modified SQP

In the Annex to the DG's report to the board of May 2005 the following data was quoted: Of the states with CSAs in place, eighty-seven had SQPs, seventy-five of which were in force and operative, i.e., the states still met the eligibility criteria; and thirty-eight SQP states had additional protocols approved by the board of which twenty were in force. However, the Board was aware that many SQP states at the time did not have diplomatic missions in Vienna and some were not members of the IAEA.

The modified text of the SQP revised the eligibility criteria for an SQP, it reduced the number of provisions of the SQP which were held in abeyance and so placed new obligations on the part of an SQP state. The eligibility criteria still included the requirement that the state had minimal or no nuclear material. However, if a state already had a nuclear facility without nuclear material or had taken a decision to construct, or to authorize construction of, a nuclear facility, the state would be ineligible to have an SQP. In such a case, instead of modifying its SQP, the state would rescind its SQP.

The new, previously held in abeyance, obligations of a state with a modified SQP included providing an initial report to the IAEA on all the nuclear material in the state, including information on the location and usage of the nuclear material, and providing design information for any planned nuclear facility). The initial report places a responsibility on the state authority designated as responsible for safeguards to identify and locate *all* nuclear material subject to safeguards[1] in the state and bring it under control. The nuclear material should be listed in the initial report and should be made available for verification during an IAEA inspection, should one occur.

The authority of the IAEA to inspect and verify nuclear material in the initial nuclear material inventory report submitted by the state was the single, most important strengthening measure of the modified SQP.

To provide some balance in the system, the ability of an SQP state to request exemption of nuclear material from safeguards was no longer held in abeyance in the modified SQP. Table 1 provides a comparison of the obligations of states under the original SQP and the modified version.

While the obligations for SQP states are uniform, SQP states vary widely. The size of SQP states ranges from less than 1 km^2 to greater than 2.1 million km^2. Their populations range from less than one thousand to more than 90 million. Some SQP states also have large-scale uranium mining activities, highly advanced industrial capabilities or plans for generating nuclear power.

Table 1. Comparison of obligations

Obligations	Original SQP	Modified SQP
Establish an SSAC	Yes	Yes
Submit initial report	No	Yes
Report import/export of nuclear material	Yes	Yes
Early provision of design information	6 months before nuclear material in a facility	Notify of decision to construct or to authorize construction of a facility
Inspections	No	Yes

For a state with a modified SQP, if it has nuclear material which is suitable for fuel fabrication or isotopic enrichment even in quantities less than the SQP limits, this inventory must be declared in its initial report, and if the state has an AP in force, site information has to be provided for each location where the material is held.

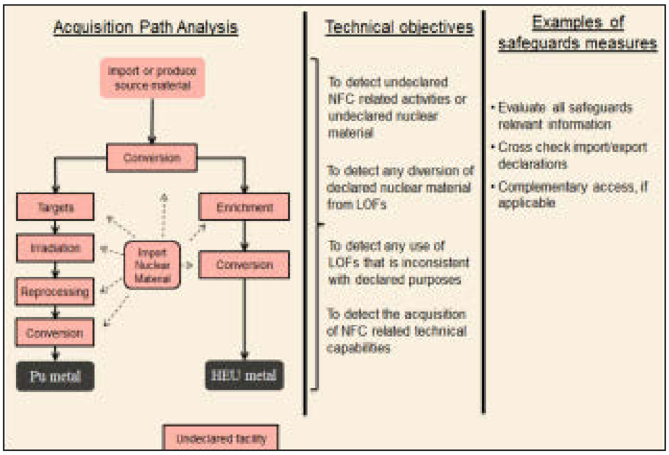
While the obligations and reporting requirements for SQP states with modified SQPs are relatively clear, what is not clear for many outside the IAEA is what safeguards activities the Secretariat performs for such states.

Safeguards Activities for SQP States

As for all other states with CSAs, upon receipt of initial and other reports—and declarations under the AP, if applicable—the Secretariat establishes and/or updates the state inventory of nuclear material. Thereafter, the state evaluation group (SEG), which is a multi-disciplinary team consisting of inspectors and analysts, performs consistency analysis on the information to determine if it is internally consistent and consistent with safeguards-relevant information in IAEA databases, such as Directory of Radiotherapy Centers (DIRAC), and information from other sources.

The SEG, having analysed all safeguards relevant information for an SQP state, will then develop or update the state-level safeguards approach (SLA), which includes evaluating whether or not there are any plausible paths for the acquisition of nuclear material suitable for use in a nuclear explosive device. In the case of an SQP state, source material could be obtained by undeclared import or undeclared production in a conventional mine or as a by-product of gold, copper, or phosphate production.

Figure 1. Example of the development of an SLA for an SQP state



Technical safeguards objectives are identified, which are focused on detecting and deterring any possible undeclared nuclear material or activities, and safeguards measures required to meet the technical objectives are identified. To detect undeclared import of nuclear material, the safeguards measures to address that objective would include the comparison of a state's import/export reports and declarations with those from other states, monitoring open sources and perhaps performing complementary access, if the SQP state has an AP in force.

The SLA development process is illustrated in Figure 1, using the example of an SQP state with no declared or known uranium mining or other nuclear-related activities. The process is exactly the same as that used for a CSA state without an SQP, but takes into account the specificity of SQP states.

In states with a modified SQP, the IAEA may perform *ad hoc* inspections to verify the information contained in the initial report and to identify and verify any changes that have occurred since the date of the initial report. As for all CSA states, a modified SQP state is notified at least seven days in advance of an inspection and of the location for the inspection. For a state with an AP, the IAEA may perform complementary access with two hours notice, when in conjunction with an *ad hoc* inspection. In all other cases, at least twenty-four hours notice is provided for complementary access.

The scale of the IAEA's in-field verification activities in SQP states is small. The number of SQP states where in-field verification activities occurred in a calendar year ranges from 1 to 4 over the past few years. The calendar days spent in SQP states for verification activities in 2014 was 29.5 days, which represents 0.2 percent of the total spent for all states.

State Evaluation and Drawing Safeguards Conclusions

The process of drawing safeguards conclusions for SQP states is the same as for other states with CSAs in force. It is designed to ensure that the conclusions are valid and based on an appropriate level of safeguards activities. The SEGs regularly evaluate all the safeguards relevant information available for an SQP state, especially information from in-field activities and the results of the SEG's consistency analysis. Its safeguards findings and conclusions are documented in a State Evaluation Report (SER). One of the assessments made is whether the state continues to be eligible to have an operational SQP. An internal committee reviews the SER and makes recommendations on safeguards conclusions to the DG who reports the Secretariat's findings and conclusions to the Board in the annual SIR.

For states with CSAs (with or without SQPs) and APs in force, there are two typical variations of safeguards conclusions:

- If the Secretariat found no indication of the diversion of declared nuclear material from peaceful activities and no indication of undeclared nuclear material or activities, the Secretariat concludes, on that basis, that **all** nuclear material remained in peaceful activities;
- If the Secretariat found no indication of the diversion of declared nuclear material, but evaluations regarding the absence of undeclared nuclear material and activities were ongoing (such as the situation where initial AP declarations had not been received), the Secretariat concludes, on that basis, that **declared nuclear material** remained in peaceful activities.

For a state without an AP, while the IAEA looks for indications of undeclared nuclear material and activities, it cannot and does not report any conclusions regarding the absence of undeclared nuclear material and activities. For these states, the formulation of the safeguards conclusion is: If the Secretariat found no indication of diversion of declared nuclear material, the Secretariat concludes, on that basis that **declared nuclear material** remained in peaceful activities.

However, the cautionary text of the SIR for 2003 still applies, i.e., for an SQP state without an AP, the Secretariat has only limited means to evaluate any potential nuclear activities in the state which might need to be declared to the IAEA, or that the state still qualifies to have an operative SQP. In addition, in the absence of an initial report, there is no declaration of nuclear material as such and therefore, drawing a conclusion regarding the absence of diversion of "declared nuclear material" remains problematic.

Challenges for SQP States

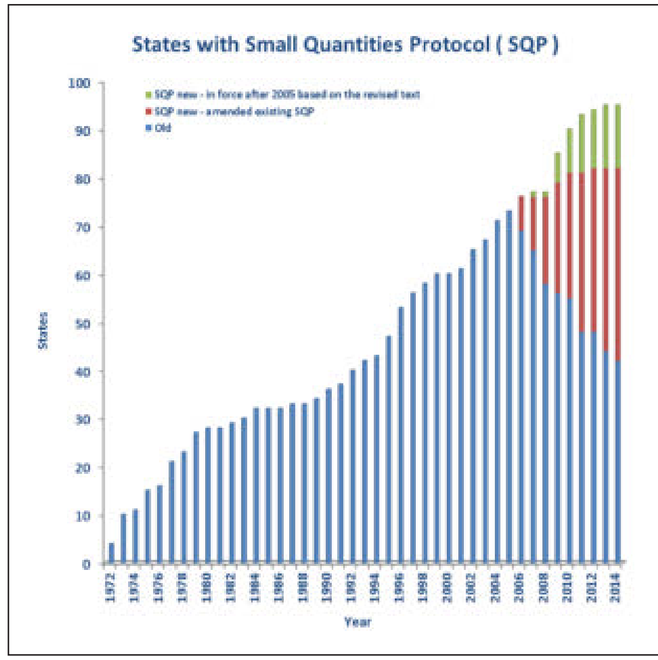
As mentioned above, in the DG's 2005 report to the board proposing modification of the SQP text, the Secretariat indicated there would be little additional cost to a state that modified or rescinded its SQP, provided that the state had a mechanism in place to monitor nuclear and other radioactive materials. The Secretariat is aware that many states with SQPs have no such mechanism in place and therefore had to establish state systems of accounting for and control of nuclear material (SSACs). To do that, many states had to undertake lengthy legal processes to establish accounting and control systems and to set up authorities to implement them.

Establishing these state authorities meant that resources had to be provided, both financial and human, which often led to competition for funds with other government bodies. In addition, many SQP states simply did not have the technical expertise available to establish and maintain a system to account for and control nuclear material.

The SIR continues to highlight concerns associated with the effectiveness of states' systems, concerns which are not confined to SQP states. However, for the ninety-five SQP states, the Secretariat considered that for many, communications with the point of contact responsible for safeguards matters were such that the efficiency of safeguards was reduced and where there was no established point of contact with whom to communicate, the effectiveness of safeguards was reduced. As in 2005, many SQP states do not have diplomatic missions in Vienna. Many SQP states lack sufficient legal structures, i.e., laws and/or regulations, to establish a functioning state safeguards authority.

To assist SQP states in understanding their obligations under their SQPs and APs, the IAEA hosts regional workshops, and supports regional and international training courses on SSACs, some of which are directed solely towards SQP states. In 2013, the IAEA published the *Safeguards Implementation Guide for States with Small Quantities Protocols* (IAEA Services Series 22) and translated it into French and Spanish. The IAEA also meets with representatives from SQP states in Vienna when opportunities arise, such as on the margins of the General Conference.

Figure 2. States with SQPs



The Way Forward

As of the end of 2014, there were ninety-five operative SQPs in force. Figure 2 depicts the conclusion of new SQPs and the rate of modification of SQPs.

For the forty SQP states which have provided their initial reports, a total of 1.24 significant quantities (SQs) of nuclear material have been placed under safeguards, of which all but 0.022 SQs was natural or depleted uranium. This is a small fraction of the material under safeguards in the world, but having correct and timely information from SQP states helps the IAEA to match global imports and exports of nuclear material, and to confirm the continued eligibility of the state to have an operational SQP.

Streamlining SQP State Reporting

Under a CSA with a modified SQP, if there are no transactions involving nuclear material in a given year, the state does not have to submit reports to the IAEA. However, under the additional protocol, there is no such relief—declarations are required even when there is nothing to declare. Such declarations are mostly compiled using IAEA software "Protocol Reporter Version 2," which is typically installed on a specific computer at the state safeguards authority.

To make additional protocol reporting as easy as possible for states with little or nothing to report, the IAEA is working on creating a web-based Protocol Reporter application that states can have access to online and prepare and submit declarations from any computer, while ensuring the integrity of the database. The web-based platform obviates the need to distribute copies of new releases of the software. There are, however, security considerations associated with web-based submissions, but none of them are insurmountable. In the future, as additional enhancements are made, the IAEA could consider developing a secure, integrated, web-based tool for SQP states that enables submittal of both nuclear material accounting reports and AP declarations to be compiled using one system, with submittals possible throughout the year as needed.

Conclusions

The modified text of the small quantities protocol has been a success in addressing the weaknesses associated with its predecessor. However, the modified SQP is only effective in so far as it is adopted and implemented by states. Recognizing that the implementation of the modified SQP may pose a challenge for some states, the IAEA offers assistance and is working to streamline reporting mechanisms and enhance cooperation with these states.[6]

References

1. Treaty on the Nonproliferation of Nuclear Weapons, INFCIRC/140, IAEA, Vienna, (1970).
2. The Structure and Content of Agreements Required in Connection with the Treaty on the Nonproliferation of Nuclear Weapons, INFCIRC/153, (Corr.), IAEA, Vienna, (1971).
3. The Standard Text of Safeguards Agreements in Connection with the Treaty on the Nonproliferation of Nuclear Weapons, GOV/INF/276, IAEA, Vienna, (1974).
4. http://www.europarl.europa.eu/sides/getAllAnswers.do?reference=E-1995-3061&language=BG (access on November 4, 2015).
5. Progress in Peaceful Applications of Nuclear Energy During the Year 1969/1970, GC (XIV)/INF/124/Add.2, IAEA, Vienna, (1970).
6. Lepingwell, J. et al. 2016. Engagement Between the IAEA Operations Divisions and State Authorities on Safeguards Implementation, *Journal of Nuclear Materials Management,* 43, 2.

The Implementation and Use of the Geospatial Exploitation System within the IAEA's Department of Safeguards

Joshua Rutkowski, Karen Steinmaus, Finn Dahl, Stephen W. Robb, and Remzi Kirkgoeze
International Atomic Energy Agency, Vienna, Austria

Abstract

The Geospatial Exploitation System (GES) is an enterprise-wide system used to analyse satellite imagery, geospatial information and associated assets for staff within the International Atomic Energy Agency (IAEA) Department of Safeguards. The GES has been deployed in the Department's isolated secure Integrated Safeguards Environment and is able to store, manage, process and securely serve geospatial data to users across the Department. The GES demonstrates the benefits of commercial off-the-shelf software integration that extends safeguards (SG) specific processes while retaining the strengths, and in cases enhances the use, of each software package while maintaining a cohesive look and feel to the interface. By employing service oriented architecture, the system is able to share and consume valuable information from disparate applications and sources from across the Department. This paper describes the last four years of effort to deploy the GES by describing the system components, applied workflows, the system IT environment and the benefits realized since deployment to users.

Introduction

One of the projects under the International Atomic Energy Agency's (IAEA) Development and Implementation Support Program for Nuclear Verification (International Atomic Energy Agency 2013) is commercial satellite imagery. The objective of this project is to develop and implement streamlined workflows and improved techniques for exploiting commercial satellite imagery and to produce imagery analysis reports and Geographic Information System (GIS) site plans in support of nuclear safeguards. The project supports the Department's Long-Term R&D Plan 2012-2023 (International Atomic Energy Agency 2012), which sets out the capabilities needed by the Department of Safeguards to achieve its strategic objectives. Included in these are the development of analytical methodologies, tools and techniques to detect signatures of undeclared activity and improve analysis of nuclear fuel cycles. Using a combination of voluntary contributions from member states and IAEA Regular Budget, the Department of Safeguard's Division of Information Management initiated a project to upgrade its imagery analysis infrastructure.

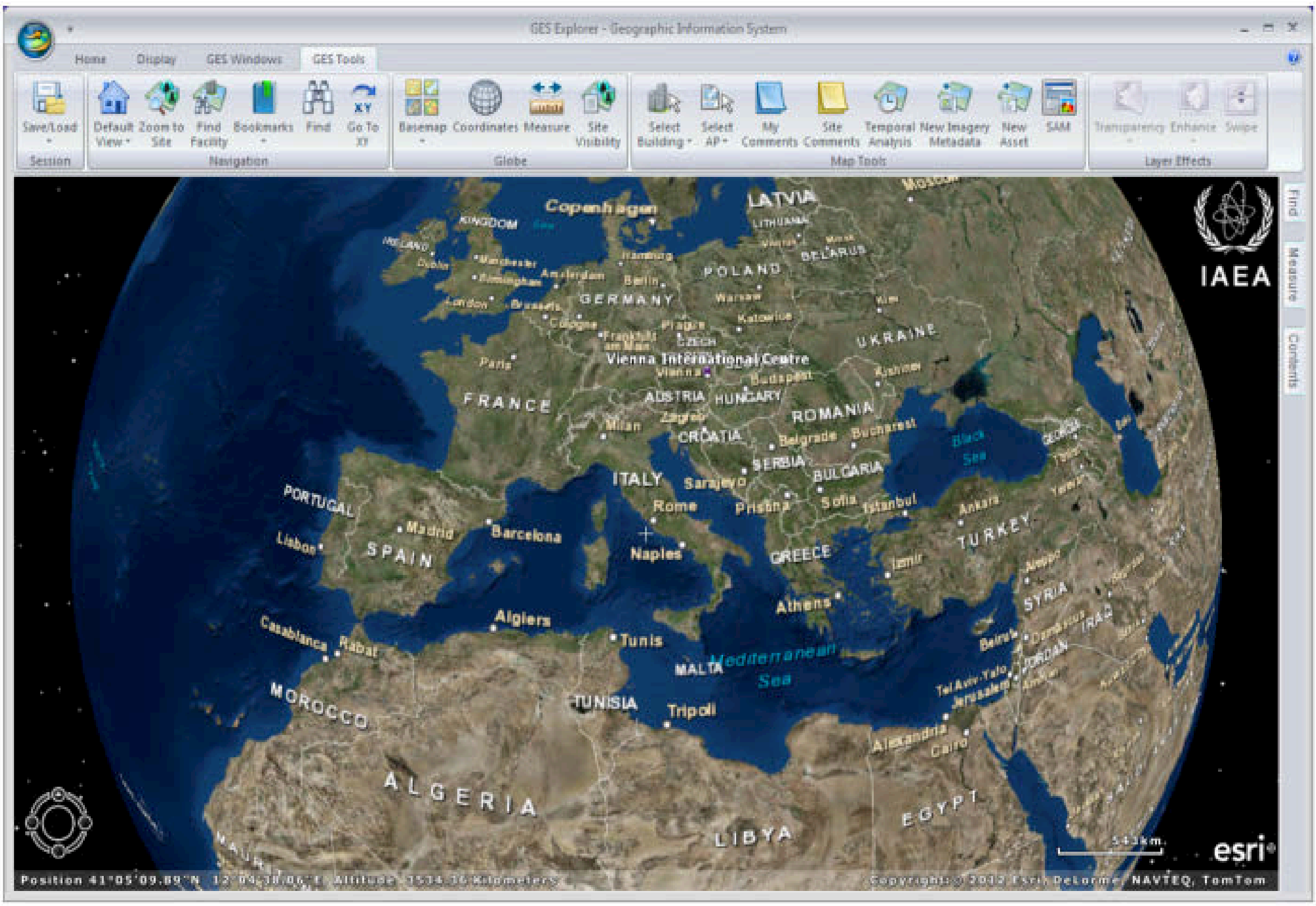
In 2009, technical specifications were developed and a competitive bid tendered for the design and development of a custom software system for the processing, storing, managing, retrieving, creation and analysis of imagery and GIS data. The requirements for the system included the ability to manage the complete image analysis cycle from initial task request through to digital report dissemination and the ability to adopt the Department of Safeguards standards for data security that provide for a robust and granular security model. In January 2010, the winning contractor was selected and a contract was awarded. The IAEA's Geospatial Exploitation System (GES) project started in mid-2010.

In December 2011, the IAEA formally accepted the GES. GES was the first analytical application specifically developed and successfully deployed into the IAEA's Integrated Safeguards Environment (ISE) – ISE is described in more detail later in this paper. GES was designed to serve geospatial data to analysts, disseminate derived products to safeguards users and make geospatial services in the form of maps and imagery available for consumption by other applications that reside within ISE. In early 2012, terabytes of Department of Safeguards' data was migrated into ISE. In mid-2012, GES deployment for users across the Department of Safeguards began with a small number of State Evaluation Groups (SEGs) and after testing the system and incorporating the results, by 2013, the system was deployed across the Department of Safeguards and made available to all SEGs.

The Use of Geospatial Information at the International Atomic Energy Agency

In the early 1990s, the United States' Land Remote Sensing Policy Act streamlined the procedure for considering license

Figure 1. The globe interface of the Department of Safeguards' Geospatial Exploitation System (GES)



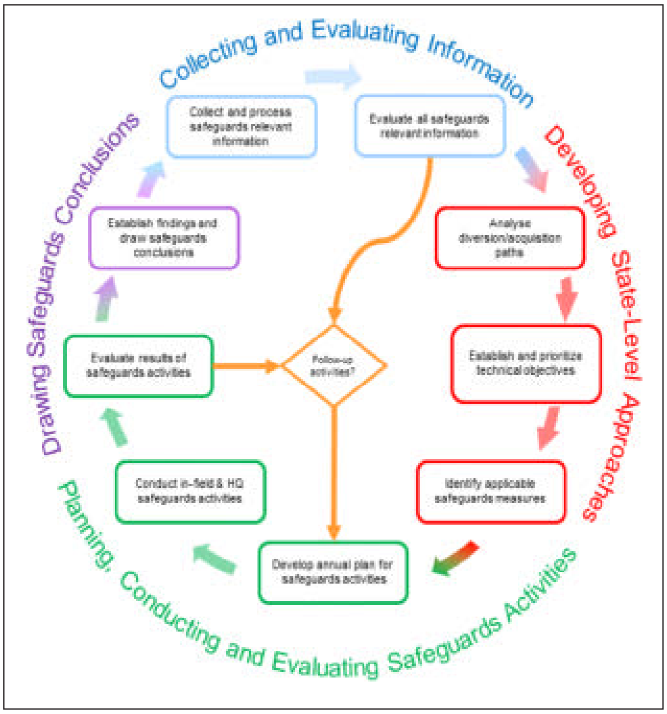
applications for commercial imaging satellites, eliminating many of the prior obstacles to such applications. Given the change in policy, the IKONOS satellite provided the public with the first access to high resolution satellite imagery. The Department of Safeguards then embarked on a series of tasks designed to investigate the potential uses of commercial satellite imagery (CSI) in support of safeguards implementation.

At the request of the Department of Safeguards, the IAEA's Office of Legal Affairs, in 1998, carried out an analysis of the legal issues associated with the IAEA's use of CSI for safeguards purposes. In its analysis, OLA endorsed the IAEA's acquisition and use of CSI for the purposes of facilitating the implementation of safeguards, citing, in particular, confirmation by the Board of Governors in 1995 of the IAEA's authority to take into account all safeguards-relevant information, including that derived from open sources (International Atomic Energy Agency 1995).

In 1999, the IAEA acquired the first high-resolution earth observation satellite image from Space Imaging's IKONOS satellite. The availability of one-meter resolution CSI meant the Department of Safeguards could, for the first time, use satellite-based sensors to clearly identify buildings and structures associated with a nuclear facility. In 2001, a CSI database of nuclear sites was created using GIS technology and by the next year came into routine use by analysts in the Department of Safeguards (International Atomic Energy Agency 2001).

The use of geographic information systems to support United Nations missions is commonplace and can be seen in a wide range of uses from humanitarian efforts, peacekeeping operations and territorial dispute resolution. The work of the United Nations Office on Drugs and Crime (UNODC) focusses on security and justice and employs GIS throughout their mission, e.g., to map areas with prevalence of criminal activities and the environmental and socio-economic conditions where these take place to plan policy interventions. The United Nations Geospatial Information Section (formerly Cartographic Section) provides geospatial and cartographic products and ser-

Figure 2. Processes to support safeguards implementation for all states with safeguards agreements



vices to decision makers in the Security Council and United Nations Secretariat, both at strategic and operational levels.[1] The Section also provides support to member states directly through international boundary projects and an inter-governmental process of a Committee of Experts on Global Geospatial Information Management (UN-GGIM).

Much has been published on the role of CSI for nonproliferation monitoring. Organizations such as the European Safeguards Research and Development Association (ESARDA) and the Institute of Nuclear Materials Management (INMM) provide forums where topics related to international safeguards are discussed and presented. These organizations are credited with publishing numerous reports in the area of satellite imagery, comprehensively addressing all aspects of remote sensing applications—from sensors to data exploitation. Avenhaus, et al.[2] presents an interdisciplinary collection of expert analyses and views of existing verification systems by providing guidelines and advice for the improvement of those systems as well as for new challenges in the field. Baker.[3] was one of the first comprehensive publications addressing the benefits and political challenges of commercial satellite imagery. Jasani[4] focused attention specifically on international safeguards and the role of satellite imagery. More recently Lafitte and Robin[5] discuss the use of satellite imagery at the European Union Satellite Center and its role in supporting decision-making for the European Union.

At the IAEA, CSI has become an important information tool for remotely monitoring nuclear sites and activities. CSI plays a significant role in monitoring nuclear fuel cycle (NFC) sites and activities, verifying states' declarations, planning and supporting verification activities, and detecting and investigating undeclared activities. The use of a GIS is critical to this endeavor as it makes it possible to combine and compare the geographic information contained within CSI with other data sources covering the same geographic extent. The use of GIS permits analysts to process, store, manage, retrieve and create geospatial data as well as analyze this information spatially.

Since the launch of IKONOS in 1999, the number and capabilities associated with earth imaging satellites has increased dramatically. The IAEA has regular access to data from more than twenty different earth observation satellites. The convergence of remote sensing, geospatial, and web technologies is creating unprecedented use and demand for GIS solutions. Open standards and interoperability between the various technologies provides possibilities to use the data cumulatively for analysis. In the declarations submitted pursuant to an additional protocol to a safeguards agreement[6] states shall submit "a general description of each building on each site, including its use …" and "the description shall include a map of the site." The modern methods for creating and maintaining site maps rely on computer aided design (CAD) or GIS software packages. As part of these declarations, the state submits a drawing or annotated image of the site. No longer is the use of geographic information a nice-to-have feature, it is a necessary component, because a vast expanse of the data landscape within the Department of Safeguards exists in a geographic context.

Many modern hardware devices collect global navigation system data or are somehow linked to a geographic location. Nuclear facility operators use such location-oriented systems to manage their facilities[7] and hold the potential to share such information through their safeguards' declarations.

The state-level concept involves the evaluation of all safeguards-relevant information in order to draw soundly-based conclusions and therefore takes full benefit from geographic information, including CSI and products derived therefrom. Typical uses of CSI in the processes supporting safeguards implementation (International Atomic Energy Agency 2013) include collecting and evaluating information and planning, conducting and evaluating safeguards activities. Another important objective of creating an Integrated Safeguards Environment is to implement a variety of analytical capabilities that will make it possible to explore complex, disparate data from different perspectives. Amongst these analytical capabilities is the GES, a powerful analytic tool that provides the analyst with an enhanced ability to undertake comparative analysis of state declarations with other safeguards-relevant information for the purpose of drawing sound safeguards conclusions.

In addition to being a tool used for the exploitation of commercial satellite imagery and other geographic information, it will also be used as a gateway to access all-source safeguards information, or at least information that is geographically referenced, and present it in a geospatial context. Examples include access to state declaration data through a reengineered Additional Protocol System (APS), the locations environmental sampling at a site or location, site photographs, open source information, etc. Future plans for enhancement of the GES include the development of a light, web-based user interface with expanded functionality and improved performance. In addition, there is a continual need to incorporate new sensors and satellite systems (e.g., satellite video) as they become available throught the commercial markets.

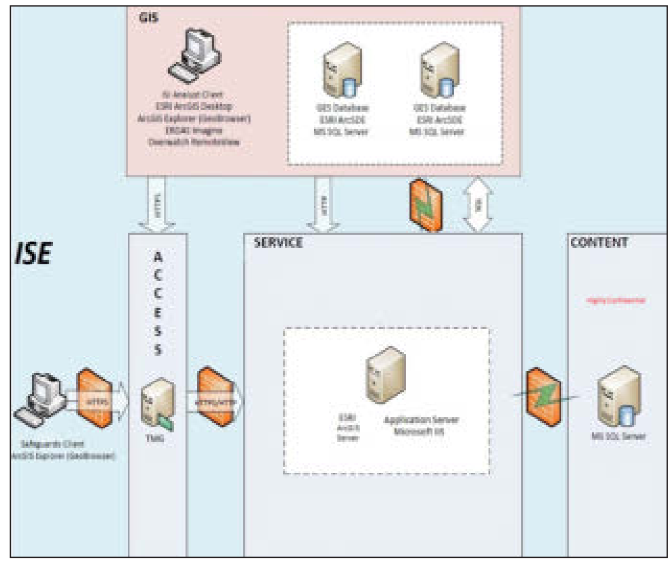
Description of the Geospatial Exploitation System (GES)

The GES is an enterprise-wide system used by Department of Safeguards' staff to process, store, manage, retrieve, and create geospatial data, and analyze this information spatially. The GES was designed to address the needs of geospatial and imagery analysts as well as provide Department of Safeguards' users with geospatial products. To enable the sharing of geospatial data and derived products, the GES uses service-oriented architecture (SOA). This section describes the GES's data and architecture as well as common workflows supported by the system.

The Department of Safeguards GES uses industry standard enterprise GIS as its core technology. The GES was designed to be deployed in the Department's secure ISE and to accommodate the Department's spatial data requirements. A description of ISE is described later in this paper.

The geodatabase stores geographic information for all of the Department's locations of interest. Imagery is managed

Figure 3. Architectural overview of the Department of Safeguards' Geospatial Exploitation System within the integrated safeguards environment



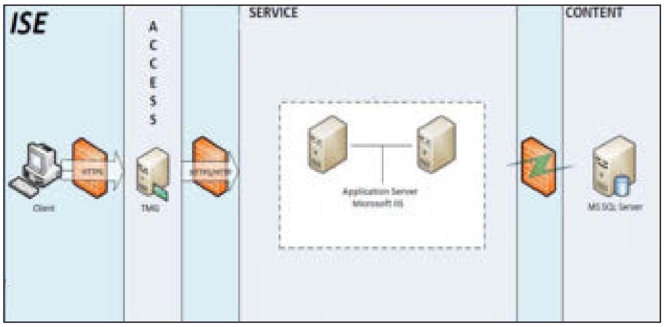
and maintained through the use of commercial off-the-shelf (COTS) server technologies.

The GES is specifically designed to allow for the integration of COTS GIS and imagery analysis technologies with other safeguards (SG) specific applications and data. COTS software provides geospatial and imagery analysts with advanced analytical software tools that are used for processing, storing, managing, retrieving, and creating geospatial data as well as analyzing this information spatially.

Not only is it important to monitor sites through time by evaluating changes in imagery, it is also important to evaluate temporal changes in the site's infrastructure. Working alongside the imagery analysts are geospatial analysts who digitize and attribute geographic information for site boundaries, buildings, utilities, etc. that are stored and maintained in the geodatabase. The geospatial analysts refer to this workflow as "site plan creation" and it includes imagery analysis, digitizing and attribution of the map data, quality assurance and dissemination. Analytical reports written by the satellite imagery analyst and any supporting documentation (relevant open source content, pictures, videos, audio, etc.) are associated with a site and are uploaded into the GES and available securely to authorized users.

The GES user interface, the Geobrowser, is used by analysts and inspectors to retrieve information on sites that they have been authorized to view. The GES is structured in such a way that it supports multiple users based on the type

Figure 4. Overview of ISE zones



of business function the user performs in the Department of Safeguards. The user's GES role is tightly coupled with their business workflow. Geospatial analysts have access and functionality to create site plans that provide the ability to associate vector features and other attributes to the buildings and infrastructure supporting a nuclear facility. Imagery analysts are able to load imagery to their preferred exploitation software in order to perform their analysis. Imagery clerks are responsible for maintaining the imagery repository, uploading metadata for satellite imagery, and maintaining records. Data clerks can upload new assets in the GES. Section heads and team leads can create new areas of interest, approve access to new imagery and carry out the workflows for approving assets and reports. Depending on their role and responsibility, other users of the GES have the ability to search and discover satellite imagery, imagery analysis reports and associated documents stored in the GES.

Description of Integrated Safeguards Environment (ISE)

Integrated Safeguards Environment (ISE) is a secure IT environment used within the Safeguards Department. The purpose of ISE is to provide a Department-wide collaborative environment, enabling people to leverage the large volumes of data that were previously stored on multiple, disconnected systems in disparate locations. ISE uses a layered architecture that enforces security and a separation of functions between the layers. There are four layers, called security zones, which in effect are independent networks separated by firewalls that control access and communication protocols.

Satellite imagery analysis reports are available on ISE as a service. The reports stored in the GES are made available to other applications in ISE. The availability of the reports as a service ensures that authenticated users are able to gain access to satellite imagery reports from various software interfaces available in ISE. For instance, the Department's "Electronic State File" use this service. The GES consumes services from some other applications on ISE products. For example, to ensure data consistency across the Department, the GES requires the use of naming conventions derived from the Safeguards Master Data.

In 2014, the IAEA reported to the Board of Governors on a project for the Modernization of Safeguards Information Technology (MOSAIC). The paper described the much-needed longer-term enhancements to the safeguards IT platform and outlined plans for achieving these objectives over a four year period. In order to implement MOSAIC, a financial commitment and support from member states as well as a step-by-step approach involving both procedural adjustments and technical tasks by the Secretariat are required. As part of the MOSAIC project, plans are in place to enhance the current GES system. Additionally, focus will be placed on improving data integration/interoperability between relevant MOSAIC applications and their datasets as referenced above.

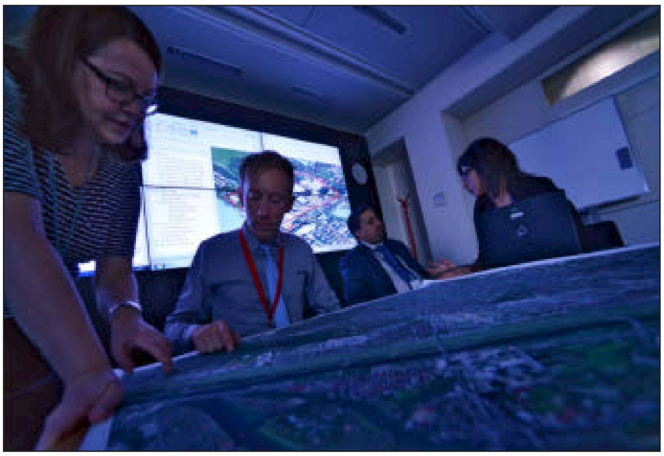
Benefits

The Department of Safeguards has deployed the GES into the Department's highly secure ISE. The GES achieved a first step toward the Department goal for deploying and integrating software applications and systems into the secure IT environment aiming to provide immediate and secure access to all available information for those who need it. Integrating the GES into the ISE environment is a significant achievement due to the complexity of the security requirements and methods necessary for protecting confidentiality. The GES provides capabilities for users across the Department to efficiently gain access to imagery and geospatial data.

GES was the first analytical capability to be deployed in ISE. Until 2012, satellite imagery analysis reports and geospatial map products were distributed in hardcopy. With the deployment of the GES, all reports, including those produced prior to its launch, are digitally disseminated and archived, and can be securely accessed through a service in the GES and other ISE applications—on a need to know basis.

The workflow for both imagery and geospatial analysts has improved since analysts can access relevant data from a single application. The GES supports the entire imagery analysis cycle from image ingest through digital report dissemination. After receipt of an image, semi-automated tools are used for preprocessing the data and generating a series of standard im-

Figure 5. SGIM analysts using geospatial data as part of a collaborative environment



age products that are ingested into the GES. Quality controls are applied at each step of the process to ensure naming conventions, metadata attributes, image display quality and site affiliation are correct. Imagery is stored in the IAEA's Secure Data Center. Keeping the imagery and analytical reports on a secure central storage, enabled the implementation of security and access control as per the safeguards policy and guidelines. The central storage also made significant improvements in the maintenance and management of geospatial, such as the critical function of backup. COTS exploitation system software is effectively integrated into the GES architecture to enable analysts to consume securely streamed image and vector data services directly from the GES.

The GES will further provide improved and secure access to other Department of Safeguards' information within a collaborative environment. Establishing such capabilities necessitates new standards to categorize and organize information, naming conventions, and further interoperability among software applications. As an example, the GES uses facility information from the Safeguards Master Data to identify the facilities on a site.

Conclusion

The Department of Safeguards deployed the GES into the Department's highly secured environment known as ISE, achieving a first step towards the goal to integrate software applications and systems and provide immediate access to all available information for those who need it. Integrating the GES into the ISE environment comes as a significant achievement due to the complexity of the access control and information security requirements. Today, the GES provides capabilities for users across the Department to efficiently gain access to imagery and geospatial data on a need to know basis. In the future, with the integration of more safeguards-relevant data and applications in ISE under the MOSAIC project, the GES will evolve, including through the adaptation of its architecture, to exploit other safeguards-relevant information such as state reports and declarations, environmental sampling locations, inspection reports, etc. Conversely, other applications within ISE may benefit from imagery, site plans, and analytic products.

References

1. Convergne, E., and M. Snyder. Geospatial Technology as a Conflict Prevention and Management Tool in UN Peacekeeping. *Amazon Web Services.* March 2015. https://s3.amazonaws.com/ipi-pdf-document-store/observatory/technology-geospatial.pdf (accessed 2015).
2. Avenhaus, R., N. Kyriakopoulos, M. Richard, and G. Stein. *Verifying Treaty Compliance.* Heidelberg: Springer Berlin, 2006.
3. Baker, J. C., K. M. O'Connell, and R. A. Williamson. *Commercial Observation Satellites: At the Leading Edge of Global Transparency.* RAND/American Society for Photogrammetry and Remote Sensing, 2001.
4. Jasani, B., I. Niemeyer, S. Nussbaum, B. Richter, and G. Stein. *International Safeguards and Satellite Imagery: Key Features of the Nuclear Fuel Cycle and Computer-Based Analysis.* Berlin: Springer, 2009.
5. Lafitte, M., and J. P. Robin. "Monitoring Nuclear Facilities Using Satellite Imagery and Associated Remote Sensing Techniques." *ESARDA Bulletin*, June 2015.
6. International Atomic Energy Agency. *Model Protocol Additional to the Agreemens(s) between state(s) and the International Atomic Energy Agency for the Application of Safeguards.* Vienna, September 1997.
7. Smith, G. "Exploiting Spatial Data for Site Declarations." *IAEA-CN-220 Book of Abstracts, Presentations and Papers*. Vienna: International Atomic Energy Agency, 2014. 119.

Development of a Prototype Fast Neutron Active Coincidence Collar for Safeguards

R. Plenteda, K. Baird, A. Tomanin, and A. Lavietes
Department of Safeguards, International Atomic Energy Agency, Vienna, Austria

J. Adamczyk
National Atomic Energy Agency, Warsaw, Poland

P. Peerani
EC-JRC-ITU Ispra

N. Mascarenhas
Comprehensive Nuclear Test Ban Treaty Organization

M.J. Joyce, M. Aspinall, and F. Cave
Hybrid Instruments Ltd., Birmingham Research Park, United Kingdom

Abstract

The International Atomic Energy Agency has developed a prototype liquid scintillator-based neutron coincidence collar in collaboration with the European Commission (EC) Joint Research Centre in ISPRA and Hybrid Instruments, Ltd. (UK). The fast-neutron detection capabilities are particularly beneficial for coincidence counting safeguards applications. Detection of neutrons from fission events does not require a thermalization process, thus neutrons coming from the same event are detected with almost zero delay. This feature makes possible the minimization of the detector coincidence gate to ~60 ns, and thus a three orders of magnitude reduction in accidentals. This enables the system to work in a low-signal condition (e.g., fast-mode fresh fuel interrogation) with an acceptable signal-to-noise ratio. This results in significantly lower measurement statistical error compared to the standard ^{3}He-based thermal neutron detectors. This activity has been partly sponsored by the UK, Netherlands, and EC Support Programs to IAEA Safeguards.

Introduction

Thermal neutron coincidence counters have been typically used in the determination of mass of safeguarded nuclear material. The high detection efficiency for ^{3}He-based detectors and their insensitivity to gamma rays have made this technology the primary one used for nuclear material assay.

One of the key mass measurements in the nuclear fuel cycle is performed at fuel fabrication facilities shortly before fresh fuel (FF) assemblies are shipped to nuclear power plants. Here, neutron coincidence counters are employed to verify the fuel enrichment as declared by the operator. For uranium FF assemblies, the low spontaneous fission rate of ^{235}U (as compared to ^{238}U) requires the use of "active interrogation" methods to assess the ^{235}U quantity in the fuel. This is typically performed with alpha-n sources, such as AmLi, whose neutron energy spectra are much softer than fission spectra.

Reactor fuel producers are increasingly using burnable poison rods (e.g., Gd, B) in fuel assemblies to increase the fuel efficiency and lifetime. While this technique is very useful for optimizing the service life of assemblies in a reactor, it directly interferes with the active interrogation technique. The correction needed to account for the presence of poison is sizable, and depends both on the amount of poison and its physical distribution. A very accurate declaration *by the operator* helps to correct the measured response, allowing for a more precise estimation of ^{235}U in the assembly, but this indirect measurement technique creates vulnerabilities to diversion scenarios.

To gain more independence from burnable poison rod declarations, a modified interrogation method is typically used. A cadmium liner is placed around the FF assembly (i.e., in the cavity of the neutron coincidence collar) to filter out all "slow" neutrons in the region of the neutron spectrum, which is pref-

Figure 1. Fission cross-sections of ^{235}U and ^{239}Pu versus Cd and Gd neutron absorption cross-sections

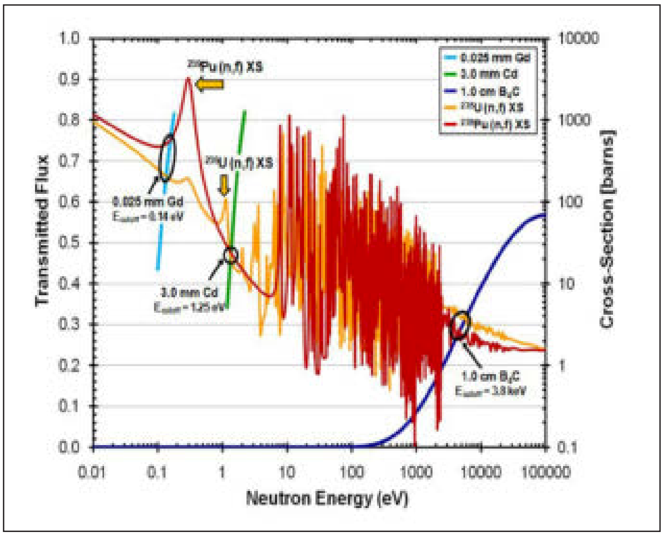
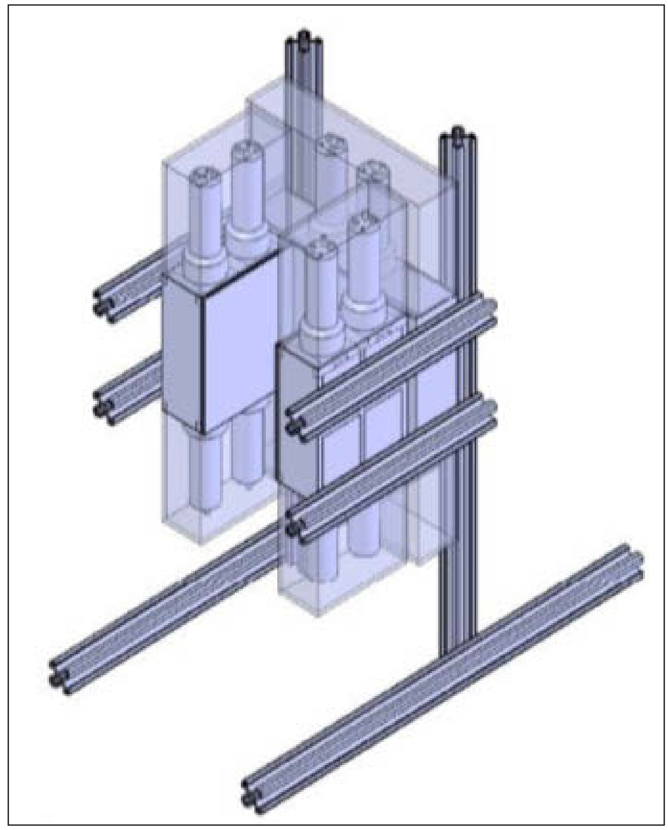


Figure 2. Prototype fast neutron coincidence collar. Not shown is the polyethylene door, which contains the AmLi interrogation source.



erentially absorbed by the burnable poisons (i.e., those below 1.25 eV). This mode of operation is referred to as "fast mode," with "thermal mode" being the classical mode without the cadmium liner. By operating in fast mode, ^{235}U is interrogated using a limited portion of neutron spectrum (above 1.25 eV), which substantially decreases the resulting amount of spontaneous fission and consequently, the detector response (Figure 1).

For thermal neutron detectors (e.g., ^{3}He-based), coincidence measurements are performed by first opening a "coincidence gate" after the first neutron is detected. The width of this gate is preset (based on analysis of the detector's response) to accept subsequent neutrons from the same fission event. This gate is of the order of 100 μs in width, and accounts for the delay in neutron thermalization before detection. For such a wide gate, the probability of accidental coincidences (the majority due to the interrogation source) is very high. The number of accidental coincidences is simultaneously estimated through the use of a delayed gate of comparable width.

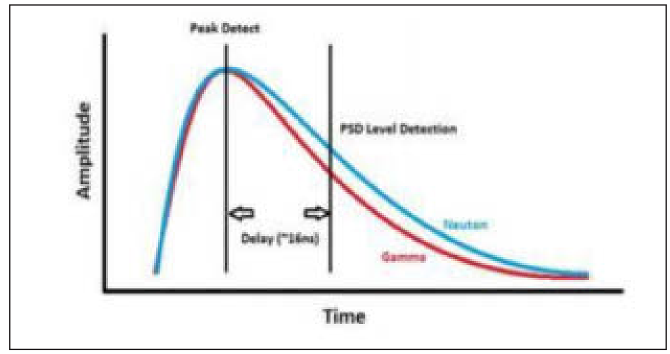
In fast mode, the ratio between the interrogating source and the induced fissions neutrons may reach 100:1 (with standard AmLi interrogation source), which results in an extremely small signal-to-noise ratio for such a large coincidence gate. In this condition, there are no satisfactory solutions using ^{3}He-based systems that can provide acceptable uncertainties (2 percent) in reasonable acquisition times (~20 minutes).

Detectors that utilize fast neutron scattering, such as Liquid Scintillator detectors, have a clear advantage in neutron coincidence measurements. For these detectors, the coincidence gate can be significantly shorter — on the order of tens of ns (i.e., 1,000 times less than for ^{3}He-based detectors) due to the immediate detection of the un-thermalized fission neutrons. Thus the number of accidental coincidences is dramatically reduced. Another benefit in using this type of detector is that the energy information of the neutron before detection is preserved, which can then be used to distinguish neutrons from the interrogation source and neutrons from induced fission.

While both the very short coincidence gate and the measured energy of the detected neutron will considerably increase the signal-to-noise ratio, and thus improve the system performance, fast neutron detectors present other challenges which need to be studied and minimized. Given an array of fast neutron detectors, the primary issues become (i) the high gamma ray sensitivity, and (ii) detector "cross talk." This paper reviews the performance of a prototype neutron coincidence counter system based on liquid scintillator fast neutron detectors, and the techniques used to develop optimal settings for gamma ray and cross talk rejection.

Figure 3. Four 4-channel mixed-field analyzers developed by Hybrid Instruments Ltd.

Figure 4. Neutron and gamma PMT pulse shape comparison for high energy gamma ray



System Architecture

The current prototype consists of twelve cubic liquid scintillator (VS-1105-21 with EJ309 scintillant) cells (10 cm on a side) that are grouped into three slabs of four cells each (Figure 2).

The design is such that the cavity can be adjusted to accommodate different types of fuel assemblies (PWR, VVER, and BWR). The collar is closed on the inactive side using a polyethylene door that contains the AmLi interrogation source. Some polyethylene is mounted around the detectors to optimize the assembly interrogation through a more homogenous moderation.

Pulse Shape Discrimination

Liquid scintillators are sensitive to both neutron and gamma ray events, and each type of interaction creates light pulses of different shapes due to the different interaction phenomena. A Pulse shape discrimination (PSD) technique is used by the acquisition electronics to differentiate the detected neutrons from the detected gamma rays. The prototype system includes three 4-channel PSD units (also referred to as mixed field analyzers (MFAs)) that were developed through collaboration with Hybrid Instruments, Ltd. (UK). The very fast electrical pulses that arise from each liquid scintillator's photomultiplier tube (PMT) are processed in real-time, then discriminated and converted into TTL output signals. This processing is done independently for all twelve channels of the collar. Figure 3 shows the four 4-channel MFAs developed by Hybrid Instruments, Ltd.[1] with support from the UK support program the fourth 4-channel unit was included as a spare.

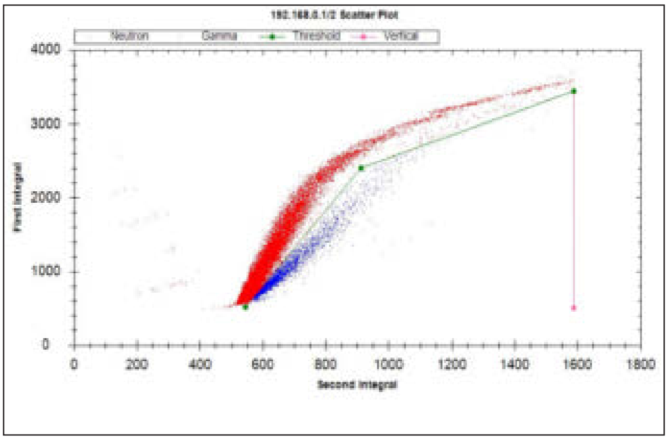
The PSD algorithm implemented in the system is based on a comparison of the integrals of the PMT pulse amplitudes. The first integral is taken from the peak amplitude, and the second integral is taken from the pulse amplitude 16 ns after the peak (Figure 4). PMT pulses that have long decay times are classified as "neutrons" by the MFA and result in a "neutron" TTL output pulse. All other PMT pulses are classified as "gammas," and result in a "gamma" TTL output pulse.

The TTL outputs of the PSD units (neutron or gamma ray pulses) are collected and sent to the data acquisition system whose key component is a National Instruments Industrial Controller (NI3110). The controller includes an FPGA-based data acquisition card and data acquisition analysis software developed by IAEA with LabVIEW. This data acquisition system and related software analysis implementation was designed and developed at the IAEA.

Figure 5 shows the typical PSD scatter plot for a californium fission source. The events above the PSD discrimination line are considered as gamma rays and below as neutrons.

To optimize the PSD discrimination line position, a study using a neutron source (^{252}Cf) and a pure gamma ray source (^{137}Cs) was performed. The results for detector efficiency and gamma ray rejection rate (GRR) for different settings of the PSD line are shown in Figure 6.

Figure 5. A scatter plot for a long measurement taken from a ^{252}Cf fission source. Each point corresponds to a single detection by one of the twelve PMTs. A three-point discrimination line has been defined, and any events located below the discrimination line (shown here in blue) are classified as "neutrons" by the MFA. All others are classified as "gammas"



On the X axis, the gamma rejection rate is shown and defined as

$$GRR = \frac{neutrons}{neutrons + gammas}$$

The operational point is determined by shifting the discrimination line to a position just before the efficiency curve rolls off due to a high false-neutron rate (gamma ray events classified as neutrons). The red point shown in Figure 6 represents a GRR of approximately $8x10^{-4}$. Here, the neutron detection efficiency is approximately 9.5 percent.

Crosstalk

In a system with twelve detectors that are placed near each other, the possibility that an incident neutron interacts in one cell, and then scatters into an adjacent cell where it interacts again, depositing sufficient energy in both is not negligible. This would result in a measured coincidence event. To reduce the probability of this kind of artificial coincidence event, known as "crosstalk," three measures were taken:

1. The detectors were physically separated by introducing 1cm of polyethylene between the cells to reduce the neutron energy after the first scatter.
2. An "anti-crosstalk filter" was implemented in the FPGA firmware of the acquisition system using LabVIEW. After the first event is detected in a given cell the filter inhibits any events within the same clock (20 ns) on the two adjacent cells that share a full face. Figure 7 is a depiction of the anti-crosstalk (ACT) filter.

Figure 6. Correlation between neutron efficiency and GRR for different PSD thresholds

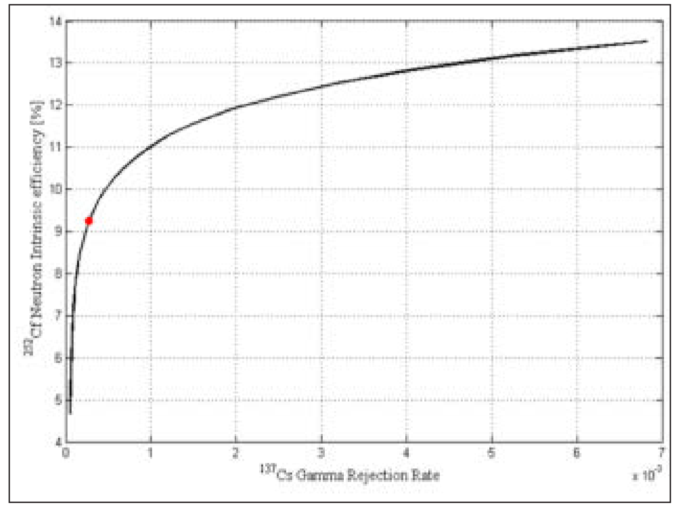
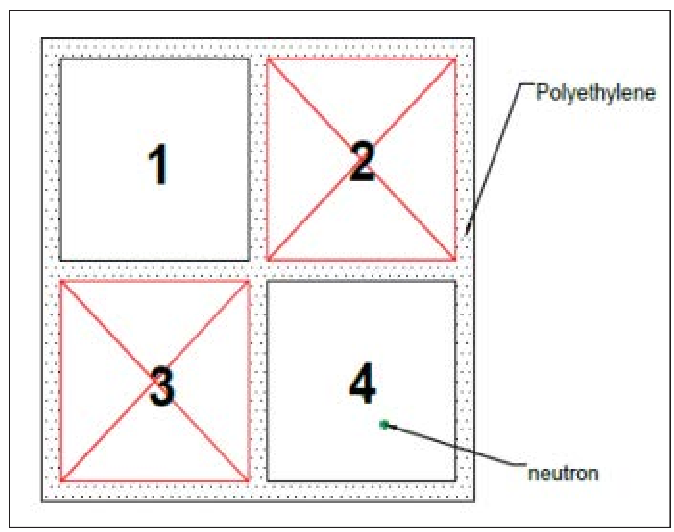


Figure 7. Concept for the ACT filter. A neutron is detected in Cell 4. Cells 2 and 3 are then inhibited to register events in the same time clock after the first event in cell 4.



3. The energy threshold is set to reduce the probability of detecting the same neutron in the second event. The optimization between this filter and the neutron efficiency has been done using a Monte Carlo simulation[2] and validated in a field test.

The ACT has been tested while activating different portions of the detector array (with adjacent or distant cells) and checking the consistency in the two configurations response (see Figure 8). Table 1 shows the test results. The test has been performed with an AmLi source in the door and a ^{252}Cf in the cavity center.

Figure 8. Different detector setups to test the ACT filter. Green indicates enabled detectors.

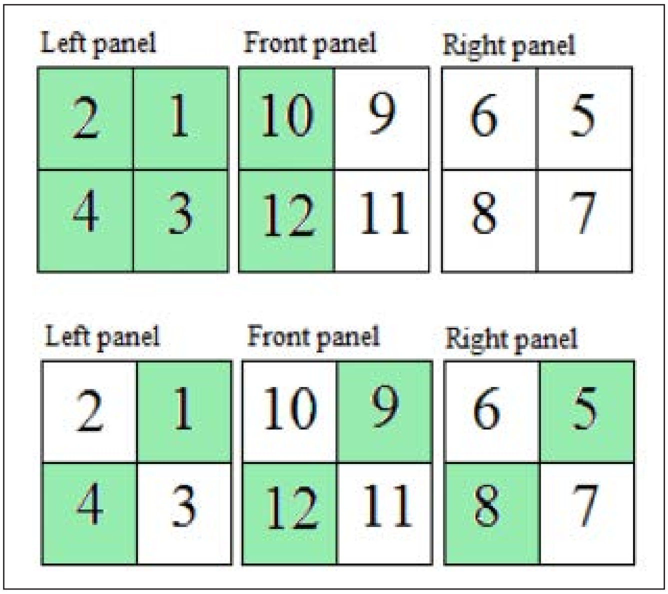
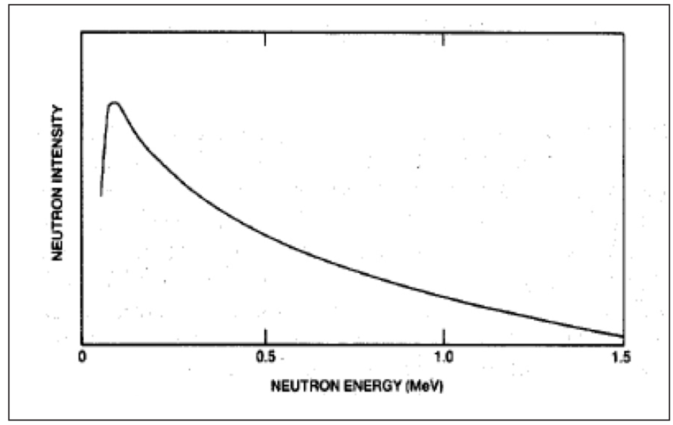


Table 1. Collar response as the function of ACT setting, for neutrons from AmLi (placed in the interrogation source position) and ^{252}Cf (placed in the centre of the collar)

	AmLi ACT off		**Cf ACT off**	
Detectors	Singles	Doubles	Singles	Doubles
All	14710	162	1000181	8063
1,2,3,4,10,12	7539	63	50464	2034
1,4,9,12,5,8	7618	13	50273	1839
	AmLi ACT on		**Cf ACT on**	
All	14773	56	98936	6419
1,2,3,4,10,12	7641	12	50315	1231
1,4,9,12,5,8	7577	17	50055	1693

Table 1 shows the successful implementation of the ACT algorithm by comparing the two different configurations shown in Figure 8. Additionally, it shows how the source position plays an important role in the crosstalk effect. A ^{252}Cf neutron, coming from the cavity center, although more energetic than an AmLi neutron, does not create appreciable crosstalk. In fact, to hit a second cell, a direction change of approximately 90 degrees is required; consequently the neutron loses enough energy to be under the detection threshold. The trajectory of AmLi source neutrons are different in that they arrive at an angle that allows them to interact with two adjacent detectors without much change in direction, and thus without much energy loss. The reduction in doubles for the Cf case is due to the ACT, which shuts down two adjacent cells then reducing the system efficiency for the second event.

Figure 9. Neutron intensity (log) versus energy for an AmLi neutron source



Even with the ACT in place, some accidental coincidences were measured. As discussed below, the combination of the ACT with a neutron energy threshold value of ~400 keV was able to reduce the cross talk contribution of the AmLi neutrons below 1 percent of the ^{235}U doubles.

Neutron Energy

For thermal neutron detectors, the discrimination between interrogating neutrons and fission neutrons can only be performed using time correlation measurements, since the energy information of the detected neutron has been lost during the moderation process. Although this time-correlation technique is still valid for fast neutron detectors, the preservation of the neutron energy information enables the use of an energy threshold to also differentiate between the two sources.

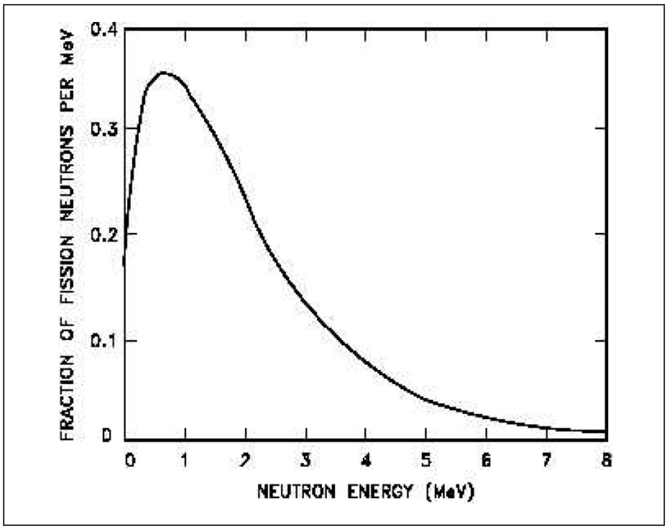
Figures 9 and 10 show the well-known energy distributions of AmLi and U fission neutrons, respectively. AmLi neutrons typically are in the energy range between 0.2 MeV and 1.5 MeV, while fission neutrons typically are in the energy range between 0 and 8 MeV with a mean of about 1.2 MeV.

An appropriately high selection of the detection energy threshold can be chosen to reduce the AmLi contribution in the neutron total rate (compared to the fission neutron rate) to a negligible level.

Simulation results[1] suggested the use of two operational threshold settings for further investigation:

1. 500 keV for coincidence counting (optimized to minimize the number of crosstalk correlations, even with the ACT enabled)

Figure 10. Fission neutron intensity (log) versus energy for an ^{235}U thermal fission



2. 1100 keV for singles counting (optimized for rejection of neutrons from AmLi, when ignoring time-correlations.)

Field Tests with a VVER 440 Fresh Fuel Assembly

A detailed experimental campaign was performed in the Atominstitut (ATI) in Vienna to characterize the performance of the prototype collar using a 3.6 percent enriched VVER 440 fuel assembly segment owned by the IAEA. Figure 11 shows this VVER assembly segment being measured in the Fast Neutron Collar.

The measured ^{235}U mass depends on the number of induced fissions generated by the AmLi source neutrons ("coupling"). It is important to correct the measurement for effects due to spontaneous fission from ^{238}U, as well as background neutrons. Therefore, at each operational setting, two separate 10-minute measurements were performed:

1. Passive detection measurement: neutron emission and detection from a fuel assembly with no interrogating source present.
2. Active interrogation detection measurement: using an AmLi source to induce fission. The AmLi source used had an emission rate of $5x10^4$ n/s.

These two measurements were repeated for two neutron measurement configurations:

a) Fast mode: with cadmium sleeves placed in front of the detectors to absorb neutrons below ~1.25 eV.
b) Thermal mode: with the cadmium sleeves removed.

Figure 11. VVER mock-up used for the field test

Each of these four measurements was performed for a different number of neutron energy thresholds, starting from the values suggested by the simulation. After an initial set of measurements, three values were chosen for further investigation:

- 263 keV – the lowest possible threshold (used for maximizing the S/N for doubles)
- 408 keV – optimized threshold (when combined with ACT, minimizes crosstalk)
- 1306 keV – used for singles

Results

The most interesting results for this campaign are summarized in Table 2.

Table 2. Subset of the VVER field test results (10 minutes measurement)

Doubles Fast Mode		
Threshold Energy (keV)	Doubles net	Err doubles
263	1388	3.24 percent
408	1252	3.33 percent
Singles- Fast Mode		
Threshold Energy (keV)	Singles net	Err singles
1306	7673	2.24 percent

Table 2 shows that in fast mode the system is able to reach, for this assembly segment with 3.6 percent enrichment, a 2 percent statistical error in approximately 20 minutes (scaled from the 10 minutes measurement) using doubles coincidence.

Counting Singles in fast mode, although producing six times higher statistics for net counts, does not improve significantly in terms of overall statistical error, as it carries the propagated error of a large quantity of singles coming from the passive measurement. Moreover, the AmLi contribution to the measured signal was estimated to be approximately 7 percent, reflecting a threshold that is still too low for satisfactory separation. Higher threshold settings would reduce the efficiency too much to be considered competitive.

As such, doubles counting is the preferred method of measurement for this configuration, as doubles are more immune to neutron misclassification than singles since the probability of misclassification for two consequent events goes with the square

$$GRR_{doubles} = GRR_{singles}^{2}.$$

Benchmark Against Conventional ^{3}He UNCL

The liquid scintillator neutron coincidence counting (LS-NCC) system participated in benchmark exercises during the second ^{3}He Alternatives Workshop in the EC-JRC-ITU Ispra in October 2014.[3]

The test focused on comparing the Fast Neutron Collar's performance against the conventional ^{3}He-based UNCL collar, in particular on measurements of efficiency (singles and doubles) and doubles counting statistics in different signal-to-noise conditions.

The passive mode was simulated using a ^{252}Cf source of 7050 n/s. Two active modes (thermal and fast) were simulated using combined AmLi/^{252}Cf sources with ratios of 10:1 and 100:1.

The Fast Neutron Collar was operated with an energy threshold at 408 keV.

Table 3 shows the difference in performance between the two systems. While the two systems have very similar neutron detection efficiencies, the fast neutron collar produces more precise measurements in all conditions due to the negligible accidental rates.

Table 3. Comparison of results for a ^{3}He-based UNCL and the LS-NCC for 10 minutes acquisition time

	^{3}He- UNCL*	LS-NCC
Singles Efficiency [percent]	10.01	9.54
Doubles Efficiency [percent]	3.23	3.43
GRR	< 1.0×10^{-8}	8.4×10^{4}
Dbls passive thermal mode	61.55±0.87 percent	67.30±0.50 percent
Dbls active thermal mode	64.78±2.05 percent	68.98±0.49 percent
Dbls active fast mode	4.07±9.77 percent	4.77±1.87 percent

* Results are not corrected for dead-time

Conclusion

The prototype liquid scintillator collar has been demonstrated to meet the performance goals (2 percent statistical uncertainties) within the target acquisition time (20 minutes) when operating in "fast mode." It has also been demonstrated that the very short gate time in coincidence counting reduces the accidental rates to a negligible level and therefore, the associated statistical uncertainties. The inherent gamma ray sensitivity of liquid scintillators is kept under control with the use of coincidence counting. Possible crosstalk effects have been studied and methods to mitigate this issue, which involve hardware and software configurations, have been developed.

The use of singles for ^{235}U fast assay has been tested, and shown to not dramatically improve the statistical precision of the U mass measurements over coincidence counting methods. Potential improvements in this direction include design changes to explore additional moderation of the interrogating source or changing the collar geometry.

References

1. M.J. Joyce, K.A.A. Gamage, M.D. Aspinall, F.D. Cave, A. Lavietes. Fast Neutron Coincidence Assay of Plutonium with a 4-Channel Multiplexed Analyzer and Organic Scintillators', *IEEE Transactions in Nuclear Science,* 61 (3) pt. 2 pp. 1340-1348 (2014).
2. Tomanin A., 2014. Development of a Liquid Scintillator-Based Neutron Coincidence Counter for Safeguards Applications, PhD thesis at the University of Ghent (ISBN 978-90-8578-753-2). 2014.
3. Peerani, P., et al,. 2015. Workshop on He-3 Alternatives for Safeguards Applications," 37th Esarda Symposium 2015.

Ensuring the Effectiveness of Safeguards through Comprehensive Uncertainty Quantification

E. Bonner, T. Burr, T. Guzzardo, T. Krieger C. Norman, and K. Zhao
IAEA Department of Safeguards, Division of Safeguards Information Management, Vienna, Austria

D. H. Beddingfield and T. Lee
IAEA Department of Safeguards, Division of Safeguards Technical and Scientific Services, Vienna, Austria

M. Laughter
IAEA Department of Safeguards, Division of Operations C, Vienna, Austria

W. Geist
IAEA Department of Safeguards, Division of Concepts and Planning, Vienna, Austria

Abstract

In order for the Department of Safeguards to provide credible assurance that states are honoring their safeguards obligations, quantitative conclusions regarding states' nuclear material inventories and activities are needed. The statistical analysis used to reach these conclusions requires that each measurement method undergo uncertainty quantification (UQ). This paper describes current work aimed at improved understanding of uncertainty sources and provides two example UQ applications, one using a top-down approach and the other using a bottom-up approach. We explore possible improvement of current top-down analysis, through a new calculation that accommodates multiplicative error models to compare operator and inspector data. To demonstrate the benefit of bottom-up analysis, we examine individual uncertainty components associated with uranium neutron coincidence collar (UNCL) measurements. Improving safeguards effectiveness is an on-going challenge and incorporating predicted uncertainties from bottom-up analyses into top-down verification measurement performance evaluations is a useful path forward to comprehensive UQ.

1. Introduction and Background

To monitor for possible data falsification by the operator that could mask diversion, paired (operator, inspector) verification measurements are assessed by using one-item-at-a-time testing to detect significant differences, and also by using an overall difference of the operator-inspector values (the "*D* (difference) statistic") to detect possible overall trends. Such an assessment depends on the assumed measurement error model and associated uncertainty components, so it is important to perform effective uncertainty quantification (UQ). These paired data are declarations usually based on measurements by the operator, often using destructive assay (DA), and measurements by the inspector, often using non-destructive assay (NDA). Statistical tests are applied one-item-at-a-time, and also to assess for possible trends by computing an overall difference of the operator-inspector values using the D statistic, commonly defined as $D = N\sum_{j=1}^{n}\frac{O_j - I_j}{n}$, where *j* indexes the sample items, O_j is the operator declaration, I_j is the inspector measurement, *n* is the verification sample size, and *N* is the total number of items in the stratum. Both the *D* statistic and the one-item-at-a-time tests rely on estimates of operator and inspector measurement uncertainties that are based on top-down UQ from previous inspection periods.

Material balance evaluations (MBE) also rely on estimates of measurement uncertainties, for every material balance area (MBA), material type, stratum, and measurement system used to verify a state's declaration. The same paired (operator, inspector) data is used for top-down UQ, applying a method known as the Grubb's estimator, or variations of it, to estimate uncertainty components. In contrast, bottom-up UQ propagates errors in all key steps of the assay to predict the uncertainty in the estimated nuclear material mass; this error propagation is similar to that used in the guide to expression of uncertainty in measurements (GUM, 2008). One step to improve UQ is to improve the bottom-up UQ so that it is in better agreement with top-down UQ.

This paper is organized into two main parts: Section 2 describes top-down UQ and gives new results for multiplicative error models. Section 3 describes bottom-up UQ using the UNCL case study.

2. Improving Top-Down UQ Applied to Paired (Operator, Inspector) Data

2.1 Measurement Error Models

The measurement error model must account for variation within and between groups, where a group is, for example, a calibration or inspection period. A typical model for additive errors for the inspector *(I)* (and similarly for the operator *O*) is

$$I_{ij} = \mu_{ij} + S_{Ii} + R_{Iij} \quad (1)$$

where I_{ij} is the inspector's measured value of item *j* (from 1 to *n*) in group *i* (from 1 to *g*), μ_{ij} is the true but unknown value of item *j* from group *i*, $R_{Iij} \sim N(0, \sigma_{RI}^2)$ is a random error of item *j* from group *i*, $S_{Ii} \sim N(0, \sigma_{SI}^2)$ is a short-term systematic error in group *i*.

The measurement error model used for safeguards sets the stage for applying an analysis of variance (ANOVA) with random effects (Miller, 1998; Norman, 2014). Neither R_{Iij} nor S_{Ii} are observable. However, for various types of observed data, we can estimate the variances σ_{RI}^2 and σ_{SI}^2. The variance of I_{ij} is given by , V(I_{ij})= $\sigma_\mu^2 + \sigma_{SI}^2 + \sigma_{RI}^2$, where the item variability σ_μ^2 is the variance of the random variable (is the true value of item *j* in group *i*, so the "item variance"). If the errors tend to scale with the true value, then a typical model for multiplicative errors is

$$I_{ij} = \mu_{ij}(1 + S_{Ii} + R_{Iij}) \quad (2)$$

where $S_{Ij} \sim N(0, \delta_{SI}^2)$ and $R_{Iij} \sim N(0, \delta_{RI}^2)$, and $V(I_{ij}) = \mu_{ij}^2(\delta_{SI}^2 + \delta_{RI}^2) + \sigma_\mu^2(\delta_{SI}^2 + \delta_{RI}^2)$, or for a fixed value of μ_{ij}, $V(I_{ij}) = \mu_{ij}^2(\delta_{SI}^2 + \delta_{RI}^2)$. Provided the magnitude of $S_{Iij} + R_{Iij}$ is approximately 0.2 or less (equivalently, the relative standard deviation of $S_{Iij} + R_{Iij}$ should be approximately 8% or less), one could convert Equation 2 to an additive model by taking logarithms, using the approximation $\log(1+x) \approx x$ for $|x| \le 0.20$. However, there are many situations for which the log transform will not be sufficiently accurate, so Section 2.2 describes recently-developed options to accommodate multiplicative models rather than using approximations based on the logarithm transform.

2.2 Grubb's Estimator and Variations for Paired (Operator, Inspector) Data

Readers familiar with random-effects ANOVA (Miller, 1998) might anticipate having repeated measurements on some of the items in order to estimate σ_{RI}^2. However, the IAEA has access to far more paired (O,I) data for which repeated measurements of the same item are not available. Therefore, this section first describes the Grubb's estimator (intended for such paired data) for additive measurement error models. Next, it describes new variations of the Grubb's estimator to accommodate multiplicative error models and/or prior information regarding the relative sizes of the true variances. Grubb's estimator was developed for the situation in which more than one measurement method is applied to multiple test items, but there is no replication of measurements by any of the methods. This is the typical situation in paired (O,I) data. We note here that the phrase "top-down" UQ is used among analytical chemists to refer to a particular type of reproducibility study that includes multiple laboratories over time measuring the same or very similar items (ISO 21748, 2010). This paper is using the phrase "top-down" more loosely, to refer to any type of empirical assessment of measurement error variances, such as in analysis of paired operator, inspector data. We also note here that the variance σ_{RI}^2 of the random error variance component R_{Iij} includes "item-specific" bias (see Section 3 and Burr and Knepper, 2005), which would not be estimable if available data were only from repeated measurements of the same or very similar items.

ANOVA with random effects based on paired data allows us to estimate the measurement error variances of plant operators and inspectors. ANOVA requires the data to fall into groups, so that within-group and between-groups variances can be defined and estimated. In this paper, the groups are the inspection periods. The basis of a Grubb's-based estimator as applied to Equation 1 to estimate σ_{RO}^2 and σ_{RI}^2 is that the covariance between operator and inspector measurements equals σ_μ^2, while the variance $\mathbb{V}(O)$ conditional on the value of *S* equals $\sigma_\mu^2 + \sigma_{RO}^2$. Therefore, the sample covariance between operator and inspector measurements can be subtracted from the sample variance of the operator measurements to estimate σ_{RI}^2 (and similarly for estimating σ_{RO}^2). That is, within a single inspection period (group) (we use lower-case *i (o)* for observed values of *I (O)*),

$$\hat{\sigma}_{RI}^2 = \frac{1}{n-1}\{\sum_{j=1}^{n}(i_j - \bar{i})^2 - \sum_{j=1}^{n}(o_j - \bar{o})(i_j - \bar{i})\}. \quad (3)$$

The estimates from Equation 3 from each of the *g* groups are averaged to get the final estimate of the inspector's random error variance, and similarly, the estimate of σ_μ^2 is the average of the sample covariances computed within each group. There is sometimes large uncertainty in the Grubb's estimates of σ_{RO}^2 and, σ_{RI}^2, particularly whenever σ_μ^2 is relatively large compared to measurement error variances (and so the sample covariance between operator and inspector measurements has large uncertainty), and/or sample sizes are small (Lombard and Potgieter, 2012). To estimate σ_{SI}^2 in Equation 1, a minor extension of random effects ANOVA shows that the expected value of the between groups sum of squares,

$$E\{\sum_{j=1}^{g} n(\bar{I}_j - \bar{\bar{I}})^2 \Big/ (g-1)\} = \sigma_{RI}^2 + \sigma_\mu^2 + n\sigma_{SI}^2,$$

so a reasonable estimate of σ_{SI}^2 is

$$\hat{\sigma}_{SI}^2 = \frac{\sum_{j=1}^{g}(\bar{i}_j - \bar{\bar{i}})^2}{g-1} - \frac{\hat{\sigma}_{RI}^2 + \hat{\sigma}_\mu^2}{n}.$$

The estimator $\hat{\sigma}_{RI}^2$ is the average of Equation 3 over all *g* inspection periods. There is no guarantee that $\hat{\sigma}_{RI}^2$ or $\hat{\sigma}_{SI}^2$ are non-negative, but the corresponding true quantities are non-negative (that is, $\sigma_{RI}^2 \geq 0$ and $\sigma_{SI}^2 \geq 0$), so various constrained versions of the Grubb's and ANOVA-based estimators can be used. Recent work is also considering Bayesian options to include prior information, such as from bottom-up UQ regarding σ_μ^2, σ_{RI}^2 and/or σ_{SI}^2, and similarly for the operator.

Recent work also extends Grubb's estimator to the multiplicative model Equation 2. Equation 2 implies that the within-group mean squared error,

$$\frac{\sum_{j=1}^{n}(I_j - \bar{I})^2}{n-1}$$ has expectation $\sigma_\mu^2\delta_{SI}^2 + (\sigma_\mu^2 + \mu^2)\delta_{RI}^2 + \sigma_\mu^2,$

where μ is the expected value of μ_{ij}, and the between-group mean squared error, has expectation $\sigma_\mu^2\delta_{SI}^2 + (\sigma_\mu^2 + \mu^2)\delta_{RI}^2 + \sigma_\mu^2,$. Therefore, both δ_{SI}^2 and δ_{RI}^2 are involved in both the within- and between-groups sum of squares, which implies that one must solve a system of two equations and two unknowns to estimate δ_{SI}^2 and δ_{RI}^2 (Burr and Krieger, 2015). The term σ_μ^2 is estimated as in the additive error model.

To illustrate numerically that a Grubb's-type estimator is sometimes needed for multiplicative models, consider an example with $g = 3$, $n = 20$, $\delta_{RI} = 0.20, \delta_{SI} = 0.02, \delta_{RO} = 0.01, \delta_{SO} = 0.005$, $\sigma_\mu = 15$, and the average true quantity is 100 units (so the true quantity has 15 percent relative standard deviation). Although three of these four relative error standard deviations are small, $\delta_{RI} = 0.20$ so the log transform will not necessarily lead to good estimation results (see Section 2.1). Using 105 simulations in R (2012) the averages of the four estimates using the Grubb's estimator without a log transform are $\hat{\delta}_{RI} = 0.202, \hat{\delta}_{SI} = 0.049, \hat{\delta}_{RO} = 0.042, \hat{\delta}_{SO} = 0.006$, , and with a log transform are $\hat{\delta}_{RI} = 0.210, \hat{\delta}_{SI} = 0.021, \hat{\delta}_{RO} = 0.042, \hat{\delta}_{SO} = 0$. For the Grubb's-type estimator modified for multiplicative models, the four averages are $\hat{\delta}_{RI} = 0.200, \hat{\delta}_{SI} = 0.020, \hat{\delta}_{RO} = 0.010, \hat{\delta}_{SO} = 0.005$ (the correct four values). In this example, the performance of these averages are repeatable across sets of 10^5 simulations to the number of digits shown, so the example illustrates that in some instances, the new Grubb's-type estimator modified for multiplicative models will be preferred.

2.3 Applying Uncertainty Estimates: the *D* Statistic

Here we provide a new result for the variance of the *D* statistic when the measurement error model is multiplicative. For an additive error model (Equation 1), it is known (Avenhaus and Canty, 1996) that

$$\sigma_D^2 = N^2\left(\frac{\sigma_R^2}{n} + \sigma_S^2\right)$$ where $\sigma_R^2 = \sigma_{RO}^2 + \sigma_{RI}^2$

and $\sigma_S^2 = \sigma_{SO}^2 + \sigma_{SI}^2$ For a multiplicative error model, it is shown in Burr and Krieger (2015) that

$$\sigma_D^2 = \frac{N}{n}\delta_R^2\sum_{j=1}^{N}\mu_j^2 + \text{Total}^2\,\delta_S^2 + \frac{N-n}{n}N\,\text{var}(\mu)\left(1+\delta_S^2\right),$$

where $\text{Total} = \sum_{j=1}^{N}\mu_j$ and $\frac{\sum_{i=1}^{N}(\mu_i - \bar{\mu})^2}{N-1}$, and so to calculate

σ_D^2, one needs estimates for var(μ) and the average of the true values, $\bar{\mu}$, plus have estimates of δ_S^2 and δ_R^2 using methods described in Section 2.2.

The multiplicative error model gives different results than an additive error model because variation in the true values, var(μ), contributes to σ_D^2 in a multiplicative model, but not in an additive model. For example, let $\sigma_R^2 = \bar{\mu}^2\delta_R^2$ and $\sigma_S^2 = \bar{\mu}^2\delta_S^2$, so that the average variance in the multiplicative model is the same as the variance in the additive model for both random and systematic errors. Assume $\delta_R = 0.10$, $\delta_S = 0.02$, $\bar{\mu} = 100$ (arbitrary units), and var(μ)=2500 (50 percent relative standard deviation in the true values). Then the additive model has $\sigma_D = 270.8$ and the corresponding multiplicative model with the same average absolute variance has $\sigma_D = 310.2$, a 15 percent increase. This 15 percent increase would lead to excess false alarms if the incorrect additive model were assumed.

2.4 Statistical Testing of Verification Data and of Materials Accounting Data

In MBE, either a single material balance (MB) or a time series of MBs is tested for the presence of any significantly large differences and/or for trends, while allowing for random and systematic errors in variance propagation to estimate the measurement error standard deviation of the MB. Similarly, in verification activities, paired operator and inspector data are also tested for any large differences and/or for trends. Therefore, both MBE and verification activities lead to the analysis of a multivariate distribution, which is usually assumed to be approximately Gaussian.

The MB is defined as MB = $T_{in} + I_{Begin} - T_{out} - I_{end}$. In MBE, the covariance Σ_{MB} of a time series of *n* material balances is an *n*-by-*n* matrix with the MB variances on the diagonal and the covariances between pairs of MBs on the off-diagonals. The entries in Σ_{MB} are estimated using error propagation applied to estimates of random and systematic error variances for each measurement method (Burr and Hamada, 2015). Although Equation 1 includes only short-term systematic errors (that are assumed constant in a given inspection period), there is still non-zero covariance between successive MBs, because ending inventory for a given balance period is the beginning inventory for the next period. Because many terms are combined and summed in each MB, it is reasonable to assume that an MB sequence has approximately a N(0, Σ_{MB}) distribution (normal with mean 0 and known covariance matrix Σ_{MB}), so tests for large single differences or trends can be based on the normal distribution. Similarly, in statistical testing of verification data, the collection of *n* paired differences, $d_j = O_j - I_j$, has a covariance matrix Σ_d whose entries are currently estimated using top-down UQ. For simplicity, the off-diagonal entries of Σ_d are currently assumed to be 0, which corresponds to assuming every d_{jj} pair is uncorrelated. The impact of estimation error in Σ_{MB} has been numerically evaluated in a few limited examples (Burr and Hamada, 2015), but have not yet been evaluated in Σ_d.

Recent work extends both one-item-at-a-time testing and *D* statistic testing to allow for any covariance matrix Σ_d, including those with non-zero off-diagonal entries. To illustrate, using the recent calculations that allow for systematic errors, we can calculate the detection probability (DP) in one-item-at-a-time testing assuming there was non-zero random error and zero systematic error and also assuming there is non-zero random and systematic error. The DP is calculated using

$DP = \sum_{i=1}^{d} P(i \text{ defects in sample})(1 - P(O - I' < A))^i$. For example, assuming three defective items, with *N* = 200, n = 50, alarm threshold *A = 3* (a false alarm rate of approximately 0.001), and δ_R = 0.23, then the DP is 0.96 if there is no systematic error, but is reduced to 0.85 if there is systematic error, with the same total relative standard deviation $\delta_T = \sqrt{\delta_R^2 + \delta_S^2} = 0.23$ and $\delta_R = \delta_S$.

3. Incorporating Bottom-Up: UNCL Case Study

IAEA inspectors rely heavily on NDA measurements to verify operator declarations, so effective UQ for NDA measurements is important. UQ can be approached either top-down by comparing the NDA result to another assay result (such as DA), or bottom-up by quantifying and then propagating the uncertainty in each step of the assay. The guide to expression of uncertainty in measurement (GUM, 2008) indirectly addresses top-down methods, but is most known for illustrating a bottom-up option that applies straight-forward propagation of uncertainty in each assay step to estimate the total uncertainty in the assay. For bottom-up UQ, the GUM writes

$$Y = f(X_1, X_2, ..., X_p) \tag{4}$$

where *Y* is the estimate of the measurand, and the *X*s are input parameters. There is recent interest in revising and extending the GUM for reasons described in Bich (2014). However, there are applications for which Equation 4 is adequate for UQ for *Y*. One simply needs to know the functional form *f*(·), and know how to quantify the error magnitudes in each of the *X'*s. To illustrate, this section focuses on the UNCL NDA method for measuring the ^{235}U content in fresh fuel assemblies. Specifically, ongoing work is highlighted that investigates how to characterize errors in each of the X's that we consider in Equation 4, and to reduce the uncertainty associated with calibration of the UNCL.

3.1 Description of UNCL

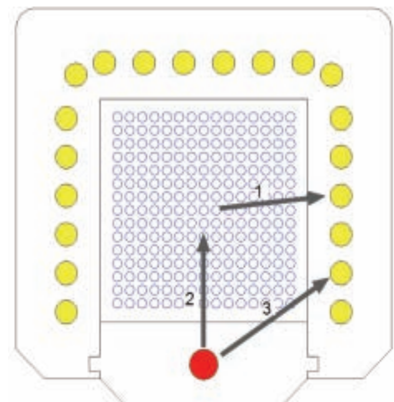
The UNCL uses an active neutron source to induce fission in the ^{235}U in fresh fuel assemblies (Menlove et al., 1990). Neutron coincidence counting is used to measure the "reals," or neutron coincident ("doubles") rate, *D* (attributable to fission events), which can then be used to determine the linear density of ^{235}U in a fuel assembly (g-^{235}U/cm) from calibration parameters, a_1 and a_2. The equation used to convert the measured *D* to *Y* (grams ^{235}U per cm) is

$$Y = \frac{kX}{a_1 - a_2 kX} \quad (5)$$

where a_1 and a_2 are calibration parameters, and $k = k_0k_1k_2k_3k_4k_5$ is a product of correction factors that adjust $D (D = X$ in Equation 2) to item-, detector-, and source-specific conditions in the calibration (Menlove et al., 1990). Therefore, Equation 5 is a special case of GUM's Equation 1, where the two calibration parameters a_1 and a_2 and the six correction factors k_0, k_1, k_2, k_3, k_4, and k_5 are among the *X's* in Equation 1. The GUM does not fully treat multi-parameter calibration uncertainties, so there are open issues in applying GUM's Equation 1 even to this relatively straightforward calibration problem (Elster, 2014). Nevertheless, it provides a practical basis to support discussion of the current practice for NDA and to describe a roadmap for more comprehensive UQ for NDA.

A schematic of a type-II UNCL with its three coupling factors is shown in Figure 1. The three coupling factors in the UNCL system are: (1) Sample-to-detector coupling (neutron doubles from fission events, reals/fission); (2) Source-to-sample coupling (fissions induced by AmLi neutron source (fission/source-neutron), and (3) Source-to-detector coupling (singles counts from source measured in detector that degrade the doubles (reals) counting statistics ($D = (D+A) - A$, $\dot{A} = (\dot{S})^2G$, where D = "reals" (actual coincidences), A = Accidentals, $\dot{A}$ = accidentals rate, $\dot{S}$= singles neutron counting rate, G = gate width for doubles coincidences)). So coupling-3 increases the *A* term, and, because $\hat{\sigma}_D = \sqrt{D+2A}$, coupling-3 is a source of uncertainty. Uncertainty evaluation suggests that detector design should maximize (1) and (2), and minimize (3).

Figure 1. A type-II UNCL with the AmLi source (red), He-3 detector tubes (yellow), polyethylene body (white) and a 15x15 PWR assembly (blue). There are three coupling factors in the UNCL system shown: (1) Sample-to-detector coupling, (2) Source-to-sample coupling, and (3) Source-to-detector coupling.



3.2 Description of UNCL Calibration and the Six Correction Factors k_0, k_1, k_2, k_3, k_4, and k_5

Menlove et al. (1990) introduced correction factors for standard PWR and BWR fuel types to adjust the measured reals count rate to the corresponding reals count rates observed in the calibration condition for a particular a_1, a_2 coefficient pair. Since that original reporting, coefficient pairs have been determined for WWER-440 and WWER-1000 fuel types (Peerani 2004).

The term k_0 accounts for uncertainty in the true Am/Li source strength, which is approximately 3.7 percent RSD based on recent IAEA estimates using 109 sources with well-known intensity ratios: 3.10 percent arises from uncertainty in the absolute source intensity of source MRC95 in a 2014 calibration and 1.95 percent arises from variation among the 109 published source intensity values, and $.0366 = \sqrt{.031^2 + .0195^2}$. Future work will partition the 3.7 percent RSD in k_0 into random and systematic components. The term k_1 accounts for uncertainty due to electronic drift (considered negligible with modern electronics, so k_1=1). The term k_2 accounts for uncertainty due to differences in detector efficiencies (approximately 1.5 percent RSD). The term k_3 accounts for the effects of burnable poisons, and k_3 depends on how many Gadolinium (Gd) rods are in the assembly, plus there is a poison pin position-dependency that leads to an item-specific bias that is not yet well characterized. The term k_4 accounts for differences in the total uranium loading (U-total/cm) between the calibration case and the measurement case. It is estimated by extrapolation from the calibration items to items having higher U loadings in modern assemblies (15x15 PWR versus 17x17 PWR). The term k_4 interacts with k_3 and adds to the Gd-correction bias. The term k_5 accounts for all other effects (e.g. spacers, bagged assemblies), but it is only occasionally used and should contribute only negligible uncertainty.

The *k*-factors allow for the use of the same a_1 and a_2 values over a wide range of measurement cases and different UNCL detector systems. The calibration factors, a_1 and a_2, and the *k*-factors aid in the identification of the error sources in the UNCL measurement and calibration. However, there is evidence of additional error sources (see Section 3.5) that are beyond our scope here.

3.3 Evidence from Top-Down UQ that UQ for UNCL Needs Improvement

Figure 2 shows that there are large relative operator-inspector differences (OID) in UNCL measurements across many MBAs and fuel assemblies. The standard deviation of the relative OIDs in Figure 2 is 8.8%, which is much larger than the RSD of the inspector's repeated measurements of the same item (approximately 1.5% in recent years). Therefore, there is evidence of item-specific bias (Burr and Knepper, 2005) and there is an opportunity for improving measurement performance that could be attained through improved UQ. Figure 3 plots the estimated relative error standard deviation

$(RSD = \sqrt{\frac{1}{n}\sum_{j=1}^{n}\{\frac{o_j - i_j}{o_j}\}^2}$) in percent and the relative mean difference (RMD= $\frac{1}{n}\sum_{j=1}^{n}\frac{o_j - i_j}{o_j}$)) in percent versus year for a particular MBA. The RSD is moderate, with one unusually large value in 2004. Plot (b) in Figure 3 suggests that the estimated RMD is trending upward in recent years toward 15%, which is larger than desired. This is an example of when a bottom-up analysis can assist with the determination of which sources of uncertainty contributed to the degraded measurement quality.

3.4 Roadmap for More Complete UQ for UNCL

There are two approaches to convert the corrected measured coincidence doubles to mass: use *k*-factors to adjust the original calibrations to the measurement condition, or calibrate the system by Monte Carlo methods for a particular fuel design. Both approaches are in use at the IAEA, and both approaches require a better understanding of the error sources in some of the *k* factors. Plus, modern fuel designs often require extrapolation beyond the original calibration uranium loadings or have more complex designs that cannot be accommodated by the use of the *k*-factor formulations. In addition, the IAEA requires calibration for fuel designs beyond the simple PWR and BWR cases addressed in the original calibration (Menlove 1990), and, it is not practical to build a representative library of reference pins/assemblies to address the complexity of modern fuel designs. Better bottom-up UQ offers the possibility of implementation of either approach.

Figure 2. Percent OID versus year for many MBAs combined

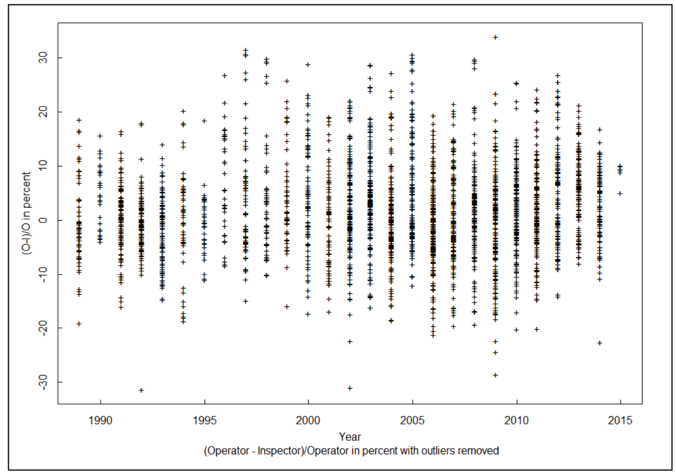
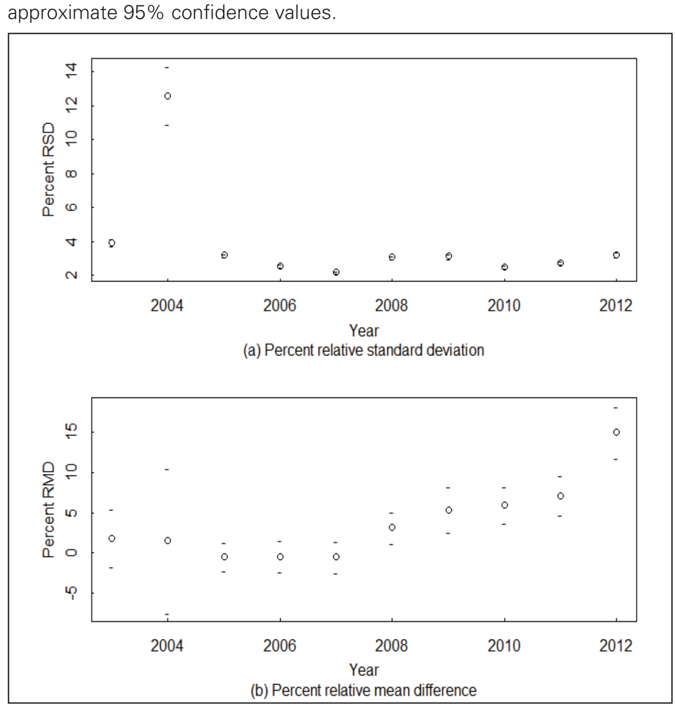


Figure 3. Percent RSD (a) and percent RMD (b) versus year for an example MBA. The dashed lines above and below each point denote approximate 95% confidence values.



3.4.1 Path 1: Calibration Using Real Data and Measured Corrections

Los Alamos National Laboratory's (LANL) original calibration (a_1, a_2) can be used with the appropriate *k*-factor values. These data were used to estimate a_1 and a_2, but were collected using lower ^{235}U linear density values than are commonly used in modern designs. In addition, the enrichment was uniform over the assembly, and the empirical Gd-poison correction employed lower poison densities than are currently in common use and assumed that the position of the poison rods in an assembly was not important. As a result of the conditions imposed by these issues, the range of application of the original calibration parameters is limited. Because it is not practical to build an assembly mock-up akin to the original LANL approach that is more representative of modern design, the use of the Monte Carlo calibration approach is gaining acceptance in the safeguards community. Some aspects to consider for choosing Path 1 (not yet fully attempted) include:

- Requires k_2 parameter and relative source intensity (source/sample and sample/detector coupling). The maintenance of detector cross-calibration terms has historically proven to be cumbersome.
- Requires use of original LANL calibration data of doubles rate versus ^{235}U for range of enrichment.
- LANL used DU and LEU pins arranged in different configurations to get relatively wide range of enrichment valid up to 3.2% ^{235}U.
- Possible to do limited poison correction via a simple model.
- Estimated $\geq$5 percent total RMSE (random and systematic) for assemblies that are well modelled by the old calibration data

3.4.2 Path 2: Calibration Using Synthetic Data

Monte Carlo methods can be used to simulate the neutron doubles counting rate for specific fuel designs. It is possible to determine values of a_1, a_2, k_2, k_3, and k_4 by simulation, but this is rarely done. It is more common to simulate the measured counting rate for a particular case or to determine a_1 and a_2 for predefined *k*-value cases (e.g., a particular fuel design including a defined poison condition).

To better understand the ability to reliably calibrate the UNCL system and apply a qualified error estimation to the calibration results, the IAEA simulated the original calibration cases presented by Menlove for the UNCL calibration for PWR and BWR fuels measured in thermal- and fast-mode with and without poison pins (twenty-seven PWR cases and thirty-four BWR cases). All cases were simulated to have a doubles rate of within one standard deviation ($1\text{-}\alpha$) of the originally-estimated measurement uncertainty ($1\alpha \sim 3.2$ percent, including counting statistics variation and the source yield uncertainty). In this case the reference fuel assembly geometry and descriptions of the standards were sufficient to confirm that the fuel assembly model represents the physical assembly with nearly negligible bias. The single largest factor impacting the simulation uncertainty was the selection of the energy spectrum of the simulated active-mode source (Beddingfield, 2015).

While modelling can produce case-specific values or generate calibration coefficients over a variety of ^{235}U loadings, this approach is vulnerable to "sample definition bias," where the actual fuel assemblies to be verified are not accurately represented in the model. Despite this potential vulnerability, we have shown that modelling can produce a useful calibration curve with qualified uncertainty values for use with real data that has equal or better performance than could be obtained from representative standards. Therefore, a Monte Carlo modelling technique is the preferred path (especially when extrapolated beyond the 3.2 percent enrichment in the original LANL calibration and/or when Gd poison and 5.5 percent enriched pins are present). Some aspects to consider for choosing Path 2 include:

- Absolute source intensity and neutron energy spectrum is needed to adjust for AmLi source strength and enable precision modelling.
- Requires design information of assembly (sometimes proprietary issues).
- Possible to adjust for poisons, gradients in enrichment, different fuel zones, etc.
- The IAEA has produced historically good modelling results.

3.4.3 Numerical Example of Error Propagation for the UNCL

We reanalysed nine pairs of (D, ^{235}U) from Table VII for PWRs from Menlove et al. (1990), fitting Equation 2 with approximately 2 percent RSD. Following Path 2 to illustrate, we then applied noise to the factor k, where $k = k_0 k_1 k_2 k_3 k_4 k_5$, to account for the departure from the calibration conditions described in Section 3.2. Figure 4 gives example RSD values for the 9 (D, ^{235}U) pairs in 10^5 simulations using the software package R (2012). In each simulation, 6 of the 9 (D, ^{235}U) pairs were randomly selected to calibrate, and the other 3 (D, ^{235}U) pairs were used to test.

Varying amounts of random error in k were applied, ranging from 1 percent to 10 percent RSD, which represents the aggregate effect of errors in each of k_0-k_5. Recall the current estimate of the RSD in k_1 is 3.7 percent and in k_2 is 1.5 percent. There is random counting error in the doubles rate D, which is simple to quantify. There should be negligible uncertainty in k_0 and k_5. However, the factors k_3 and k_4 interact in complicated ways that are not yet fully understood. It is also not yet fully understood how to partition the errors in the k_1,k_2, k_3, and k_4 into random and systematic errors (see cases 1-3 in the next paragraph). Also, there are options to accommodate errors in predictors (the predictor is kD in Equation 4) that are under investigation.

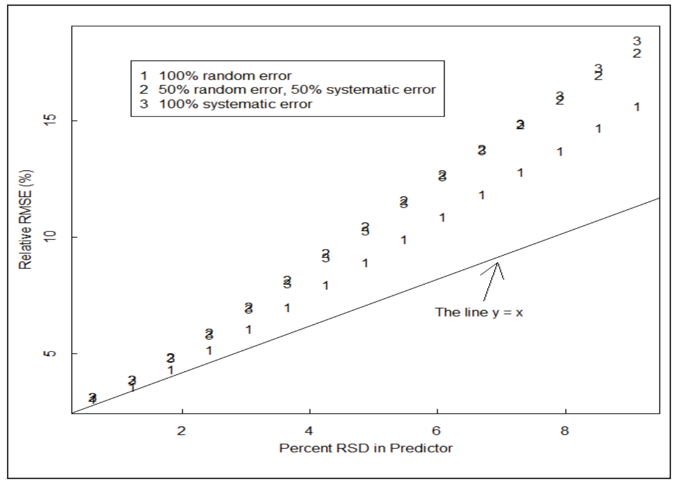
Figure 4 plots the percent relative root mean squared estimation error in estimating y for a range of RSD values in the predictor kD (from near 0 percent to 10 percent) for 3 cases. Case 1 assumes that all errors in kD are random. Case 2 assumes an equal partitioning of total error into random and systematic. Case 3 assumes all errors in kD are systematic. Figure 4 includes the effect of error in calibration constants a_1 and a_2 as well as random and/or systematic errors in kD.

3.5 Discussion

Assay challenges associated with new fuel and poison loadings have motivated synthetic calibration of the UNCL with Monte Carlo codes and this has led to a closer analysis of UNCL uncertainty components. The k factors k_0, k_1, k_2, k_3, k_4, and k_5 have been used for UNCL calibration and UQ for many years. However, there are recent assay challenges associated with new fuel and poison loadings, so the errors in the individual *k factors* are under investigation. Also, there are several other effects that are not captured by the k factors that MCNP modelling suggests are important, including:

- There is a bias associated with sample position in the detector, particularly for BWR measurements.
- The Gd poison correction should be modified to account for varying enrichment of the pins.
- Beddingfield (2015) shows that the AmLi sources exhibit radial anisotropy in source strength (up to 1 percent variation in the apparent source strength as it is rotated in its holder), which can be compensated for using a normalization feature in the UNCL software, but if an inspector rotates or temporarily removes the source between the time of normalization and the assay, a bias can result when inspectors recalibrate the UNCL in the field.

Figure 4. The RSD in UNCL prediction versus RSD in the predictor kD on the basis of 10^5 simulations. The data are the nine data pairs from Menlove et al. (1990). The nine D values are 111.1, 132.0, 149.7, 158.8, 164.1, 173.4, 176.0, 180.8, 186.5. The corresponding 9 ^{235}U values are: 16.20, 21.89, 27.59, 29.37, 31.15, 33.28, 34.71, 36.84, 38.98.



- The UNCL assay is sensitive to the positioning of the fuel assembly inside the UNCL and care needs to be taken to keep the fuel assembly in the same position as was used during calibration. Other simple sources of uncertainty include the assay counting time and differences in background between the calibration and the assay.

Inspector training for NDA includes top-down UNCL results such as those in Figures 2 and 3. The IAEA training section believes it is important for inspectors to understand the assembly design and INCC input requirements. Incorrect INCC declaration input, which might be thought of as a "human factor," is thought to be among the largest contributors to the observed UNCL uncertainty. This is an additional error source that is not included in the k factors, and should not be, because with better training, inspectors will provide correct INCC input.

4. Summary

Through the combined efforts and observations of inspectors, statistical analysts, NDA experts, and training officers, we have a better understanding of how more comprehensive UQ can be applied to improve statistical analyses conducted by the IAEA. Using examples that describe the challenges associated with quantifying and identifying sources of uncertainty, we have described on-going efforts to improve the currently used top-down analysis and have also incorporated a bottom-up assessment of individual uncertainty components.

By exploring uncertainty components from both top-down and bottom-up approaches, we can see how promoting comprehensive UQ can reduce measurement uncertainty and in turn improve safeguards. Recent work extends top-down UQ to accommodate multiplicative error models and known constraints on the true measurement error variances. Other recent work on bottom-up UQ was illustrated with the UNCL case study, where better understanding of uncertainty components of the adjustment factors (the *k*s in Section 3.2) is a first step toward quantifying how to reduce uncertainty in current UNCL measurements on new types of fresh fuel assemblies.

Finally, one tends to "believe" the result of top-down UQ more when it is in conflict with bottom-up UQ; however, the additive model in Equation 1 (and similarly, the multiplicative model in Equation 2) assumes, $S_{li} \sim N(0, \sigma^2_{Sl})$ with σ^2_{Sl} constant over inspection periods, which is a strong assumption that is not always true; so top-down UQ also requires careful scrutiny.

References

1. Avenhaus, R., Canty, M., *Compliance Quantified*, Cambridge University Press, 1996.
2. Beddingfield, D., *Simulation and Modeling of AmLi Sources for IAEA Safeguards Applications,* SG-RP-13454, 2015.
3. Bich, W., Revision of the Guide to the Expression of Uncertainty in Measurement. Why and How, Metrologia 51, S155-S158, 2014.
4. Burr, T., Hamada, M.S., Bayesian Updating of Material Balances Covariance Matrices Using Training Data, *International Journal of Prognostics and Health Monitoring,* 5 (1) 006, 13 pages, 2014.
5. Burr, T., Hemphill, G., Multi-Component Radiation Measurement Error Models, *Applied Radiation and Isotopes* 64(3): 379-385, 2006.
6. Burr, T., Knepper, P., A Study of the Effect of Measurement Error in Predictor Variables in Nondestructive Assay, *Applied Radiation and Isotopes* 53(4-5): 547-555, 2000.
7. Burr, T., Krieger, T., *Grubbs Estimators in Multiplicative Error Models,* 2015.
8. Elster, C., Bayesian Uncertainty Analysis Compared to the Application of the GUM and its Supplements, *Metrologia* 51, S159-S166, 2014.
9. Favalli, A., Croft, S., Swinhoe, M., Perturbation and Burnable Poison Rod Corrections for BWR Uranium Neutron Collar, *Proceedings ESARDA*, 2011.
10. Guide to the Expression of Uncertainty in Measurement, JCGM 100: 2008, www.bipm.org
11. ISO 21748:2010 Guidance for the Use of Repeatability, Reproducibility, and Trueness Estimates in Measurement Uncertainty Estimation.
12. Jarman, K., Smith, E., Wittman, R., Zalavadia, M., Croft, S., Burr, T., Uncertainty Analysis for Non-Destructive Assay with Application to an On-Line Enrichment Monitor, ANS MC2015 - Joint International Conference on Mathematics and Computation (M&C), Supercomputing in Nuclear Applications (SNA) and the Monte Carlo (MC) Method, Nashville, Tennessee USA 2015.
13. Lombard, F., Potgieter, C. Another Look at Grubbs Estimators, *Chemometrics and Intelligent Laboratory Systems*, 110(1),74-80, 2012.
14. Menlove, H., et al., Neutron Collar Calibration and Evaluation for Assay of LWR Fuel Assemblies Containing Burnable Neutron Absorbers, LA-11965-MS (also ISPO-323), 1990.
15. Miller, R., Beyond ANOVA: *Basics of Applied Statistics,* Chapman & Hall, 1998.
16. Peerani, P., Computational Calibration of UNCL Neutron Collars for Fresh Fuel Elements, Technical Note I.04.142, European Commission Joint Research Center, 2004.
17. R Core Team R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria, www.R-project.org, 2012.

Dispersion of Particles on Flat Substrates for Microprobe Analysis

N. Dzigal
International Atomic Energy Agency and Vienna University of Technology, Vienna, Austria

E. Chinea-Cano
International Atomic Energy Agency, Vienna, Austria

Abstract

This contribution proposes a shockwave dispersion method for sample preparation in safeguards analytical practice. It compares this method to conventional sampling techniques of environmental swipes and uses a range of statistical methods to evaluate the dispersion quality of seven procedures. A major part of this paper involves image analysis of optical and scanning electron microscope (SEM) images using Fiji software and plugins, as well as the handling of large data sets that are typical of modern imaging systems. Images were acquired by a Zeiss Z2m optical microscope and a Tescan Lyra3 SEM.

Introduction

Microprobe beams have a wide spectrum of applications that range from industrial applications (such as welding, cutting, and manufacturing) to scientific research (geology, biology, biochemistry, physics, medicine, and forensics). These techniques have established themselves in the field of single particle analysis whereby micrometer-sized artifacts are investigated for the purpose of extracting morphological, chemical, isotopic, and provenance information.

Particularly, particle analysis for safeguards applies a range of techniques to verify the completeness of declarations of nuclear activities in both research and production facilities. These particles are collected on pieces of cotton cloth (TexWipe®, TX304) by swiping surfaces of safeguard interest. Specifically, these particles may provide evidence of undeclared, singular enrichment events or treaty-prohibited research endeavors.

Microprobe Techniques and the Need for Dispersion

Particles from swipes vary typically in size from sub-micron to ~100 µm in diameter with an average of about ~10µm (including particles of interest and matrix particles). Each particle carries a wealth of information, and for that reason it is vital to prevent mixing of chemical signatures of particles of interest and environmental particles. Hence, to avoid collecting data from more than one particle at a time, it is necessary that the particles are separated physically and that the microprobe used is of comparable size: smaller than the inter-particle distance. This parameter can be adjusted during sample preparation and includes a two-step process where the particles are extracted from the original swipe, redistributed onto a new substrate, and then characterized using microprobe techniques. Some procedures will be biased toward a certain size range of particles, others will suffer from particle clustering and/or lack of reproducibility.

Once the particles have been extracted from the environmental swipe and dispersed on a substrate, numerous microprobe techniques are used to investigate their properties. It is important to disperse the particles on a flat and smooth surface. Depending on the nature of the information wanted, the analyst will select a suitable micro-probing technique. Furthermore, to make use of the intrinsic capabilities of any microanalytical technique, the particles should be separated by at least the spatial resolution of the technique.

Quality Control of Dispersion Method

In this paper, the applicability of the shock wave disperser is investigated. The dispersion quality of this method was compared to some features of merit of several existing methods by acquiring images of each dispersed sample and processing these using standard Fiji software and software plug-ins.

The assessment of the quality of the dispersion in this paper was performed using seven criteria listed below in order of increasing complexity:

1. Visual assessment of the particle distribution using 3D surface plots;
2. Line profiling across the diameter of the sample distribution;
3. Assessment of the circular azimuthal average of particle sizes;

Figure 1. An inertial impactor used at the IAEA Seibersdorf Clean Laboratory

Figure 2. Deposition of particles using an inertial impactor for LG-SIMS samples at IAEA

4. Assessment of particle density along evenly spread concentric circles around the geometrical center of deposition;
5. Granulometry: a numerical sieving technique for grouping particles by size;
6. Uniformity and completeness of the particle size distribution (after collection and re-dispersion); and
7. Nearest neighbor distances.

Of the above criteria, the final two from the list are given precedence in evaluating the dispersion quality since obtaining an even distribution of particles is just as important as unbiased sampling.

Standard Dispersion Methods

Established dispersion methods include sprinkling of particles onto a substrate, mixing the sample with a liquid to create a suspension or slurry and pipetting this mixture onto a substrate, or filtration of particles from liquids or gases. Usually, collection substrates have an adhesive deposited on their surface to collect and fix particles in place so that they do not re-disperse or bounce off the substrate. Currently, the inertial impaction method enjoys a preferential place as the particle extraction and dispersion of radioactive materials since the both operations can be performed within a glove bag. This minimizes the cross-contamination risks associated to sample preparation.

The Basics of a Shock Wave Disperser (Sod's Tube) [1, 2, 3, 4]

The physics of Sod Shock Tubes is well-known and has been used widely in industrial applications, investigations of shock wave behavior, and research of fluid dynamics and chaos theories.

Figure 3. Schematics of a basic shock tube

Essentially, a Sod shock tube is a tube, with a diaphragm used to separate two sections of high and low pressure (Figure 3). A shock wave is produced by the sudden removal of the diaphragm either by means of a small explosion (blast-driven) or

Figure 4. (left) Basic dimensions of the shock tube with cylindrical sample holder

Figure 5. (right) Basic dimensions of the shock tube with conic sample holder. Note sample holder slide (dark blue) which is fixable along the driven section and enables sampling at varying heights.

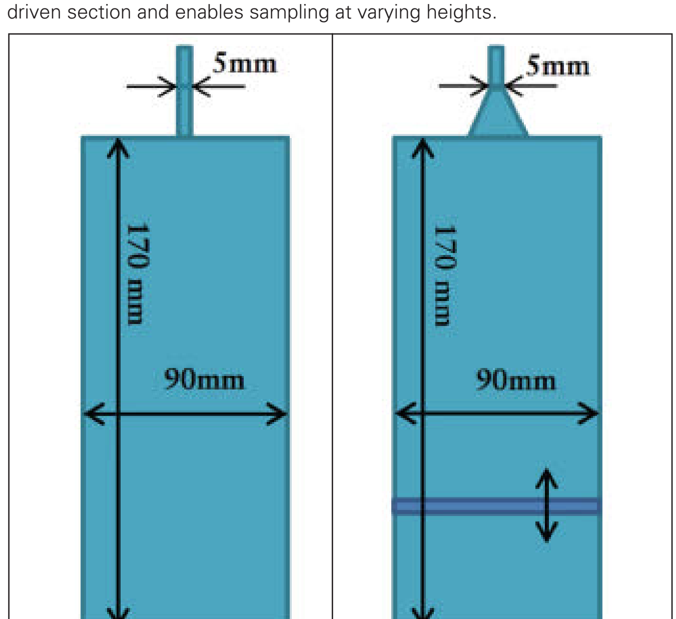


Figure 4 Figure 5

Figure 6. Prototype of shock wave disperser device

by building up the pressure in either section, eventually causing the diaphragm to burst. After the explosion, a shock wave propagates through the length of the tube until a state of thermodynamic equilibrium is reached. The high-pressure section is typically called the driver section and the low-pressure region is called the driven section.

A shock wave disperser based on the Sod's tube operation was designed and built. The details of the disperser are being published elsewhere. Essentially, the design of the driven section was optimized to maximize the spreading of particles and to minimize the time needed for the system to stabilize, which had the further advantage of producing a compact dispersion device. The driver section was constructed to have a much smaller volume than that of the driven section (Figure 4, 5, and 6) thus minimizing both the amount of sample and the presence of secondary shock waves. Furthermore, the collection substrate was coated with a thin layer of adhesive to reduce particle bouncing and resuspension by the reflected shock waves.

Dispersion Simulation

A very basic simulation of the experimental setup was performed using CAD-FEM[1] software. The aim of this simulation was to assess the behavior of the ideal shock wave in the dispersion device. Movies of the simulation, conditions, and screenshots can be found in the online version of the CAD-FEM paper.

Experimental Setup

Sample Preparation

Images using reflected and transmitted light were acquired of substrates for particle collections, which were transparent (quartz disc, 1" x 1/16", polished, Product No: 16001-1, Ted Pella Inc.). For the acquisition of SEM images, high-quality polished carbon discs of 25mm diameter were used (Hitachi, Japan). The SEM samples were coated with a thin layer of gold to minimize charging effects.

The samples were prepared in a clean room environment. The test material used was IAEA Soil 7 [6, pp. 1-2] [2, pp. 1-2]. The loading of reference material on the shock wave disperser, the sprinkled, pipetted and slurred samples was consistent ~ 36 ± 1.5 µg (note that depending on the method, not all material was deposited onto the sample collector). High-quality quartz substrates (the aforementioned discs from Ted Pella) were cleaned in an ultra-sonic bath and then depending on the method, were either allowed to dry and left clean or coated with clear varnish (Daler-Rowney Ltd, Bracknell, Berkshire, USA) or with a polyisobutylene (PIB)/nonane mixture (8mg/5ml PIB/nonane, diluted 20x) by means of a spin coater. The substrate was left clean for making pipetted, slurry dispersion, and electrostatic impactor samples but was coated with varnish for shock wave disperser and sprinkling. For the inertial impactor it was coated with a PIB/nonane mixture.

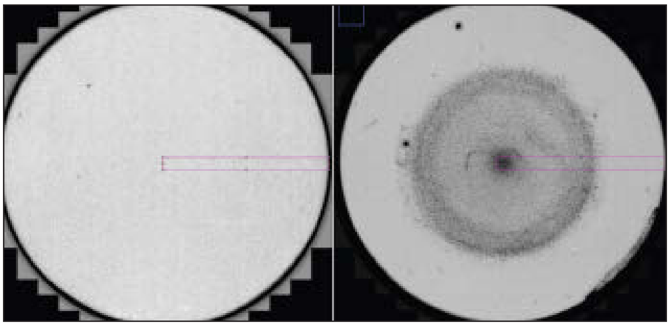
Image Acquisition

Modern imaging instruments are capable of producing large amounts of data. However, post-processing software and computer processors are limited and in this paper, we propose a compromise as follows:

Optical Images

The optical microscope used was a Zeiss Z2m with its accompanying software to acquire high-quality large-area images of the whole sample with a resolution of ~1.3 µm/pixel (See Table 2 for large area images). Up to 350 individual images taken at 5x magnification (1.268 µm/pixel resolution) were used to build the fused whole sample image. The objective used was an EC Epiplan-Neofluar 5x/0.13 HD M27 with a working distance of 15.1 mm. The images were stitched by the native AxioVision SE64 software using stage coordinates and an image overlap

Figure 7. Stripe areas of which SEM images were later taken. Left is a shock wave disperser sample, right is an inertial impactor sample.



of 10 percent. No filtering was conducted to enhance image features and the images were only corrected for background illumination during the acquisition (flat-field correction). Optical microscope images (1-1.2 GB) were acquired in less than fifteen minutes and were subsequently processed using a Fiji plug-in in less than an hour.

SEM Images

The SEM images were taken at TESCAN s.r.o., Brno, Czech Republic, on a Lyra3 FIB-SEM instrument and achieved ~0.3 µm/pixel resolution. Stitched panoramas of individual images of a 1mm x 13mm stripe along the radius of each sample were prepared (200µm before the geometrical center and 300 µm over the edge, Figure 7). The final panoramas were 300-400 MB in size and took two hours to obtain as well as about twenty minutes to stitch offline. Individual images were of an area 102,4 x 102,4 μm^2 (512 x 512 $pixels^2$). Samples of the inertial impactor and shock wave disperser (with both cone and cylinder heads) were taken for comparison.

Image Processing Software

The image processing software FIJI[3] was used to obtain distribution evaluations based on five image processing strategies extracted from data obtained by the following plugins: Interactive 3D Surface Plot[4], Plot Profile[5], Azimuthal Average[6], Concentric Circles[7], Granulometry[8], and Delaunay Voronoi[9]. The image size limit for processing by FIJI for all practical purposes was set at 1GB.

Results and Discussion

In the ideal case, one would measure the size of and count all particles from a sample to determine the particle size distribution. This may be impractical due to limitations of most image processing software, reproducibility of dispersion method and the spatial resolution achievable by instruments. This contribution aims to achieve a compromise for evaluating the dispersion quality of various sampling methods for a specific analytical purpose.

The discussion on the dispersion quality in the following sections will focus on resolving particles apart by using either optical or electron microscopy imaging techniques. The optical images, as was stated before, attained a resolution of 1.3 µm/pixel whereas the electron images achieved a resolution of 0.3 µm/pixel. These resolutions were deemed acceptable for the task at hand. However, due to the software memory constraints, panoramic SEM images of a maximum area of (1mm x 13 mm) were manageable and therefore used for small artefact distribution assessment. On the other hand, whole sample light microscopy images could be processed and were used for large-scale particle distribution analysis.

Large-scale particle distribution evaluations also contain optical images of shock wave disperser sample collection substrates at different distances from the cone/cylinder head. This was done to investigate the device and compare the cone and cylinder sample holder heads' dispersion patterns, as well as their evolution with respect to sampling distance.

Large-Scale Particle Distribution Evaluation

Surface Plots

2D and 3D plots were drawn by using the FIJI/ImageJ surface plot plug-in that translates grey level intensities of pixels to 2D and 3D color map surfaces.[4] From the plots shown in Table 1, one distinguishes easily between trivial (pipetted, slurry dispersion, and sprinkled) and mechanical (electro-static impactor, inertial impactor, and shock wave disperser) sample preparation techniques by presence of particle clusters. White areas are particle aggregates composed of clusters of indistinguishable particles.

Line Profiling

For each of the samples, a line profile across the diameter was taken as an initial assessment of particle dispersion.[5] It was found that mechanical techniques produce symmetrical particle distributions around the center of the sample disc. Further statistical strategies needed to be considered since a single line of data is not sufficient for drawing definite conclusions. However, it was a good indicator of the inherent symmetric nature of mechanical dispersion techniques. For example, the shockwave disperser method produced Gaussian particle distributions across the diameter of the substrate. Both the cone

Table 1. 2-D and 3-D surface plots of all samples

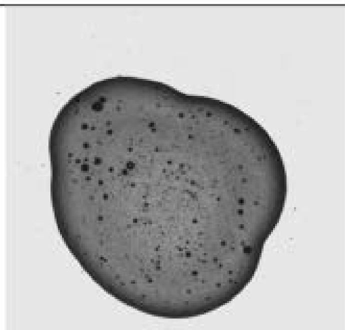
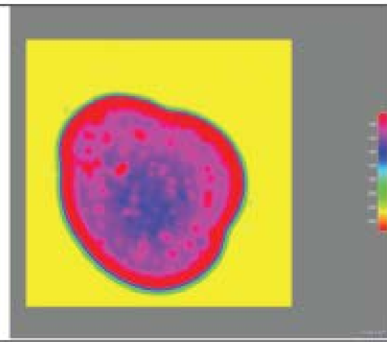
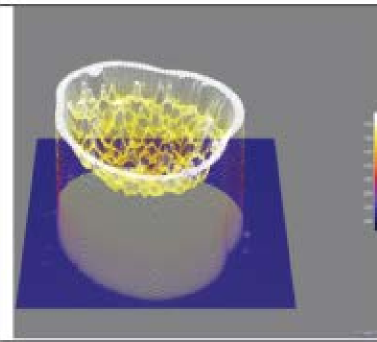
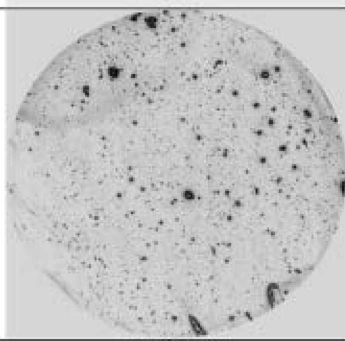
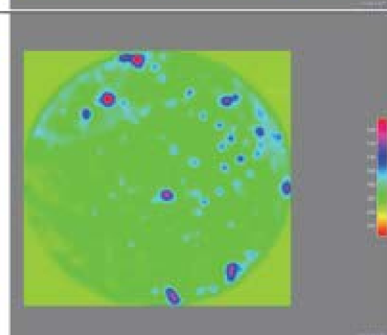
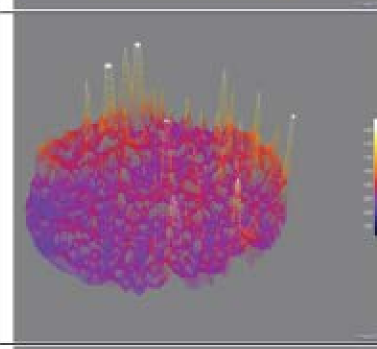
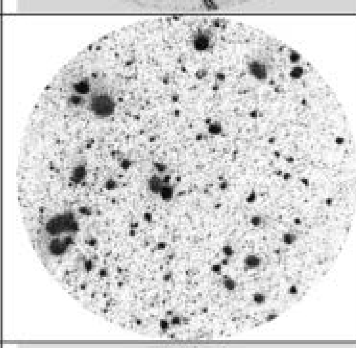
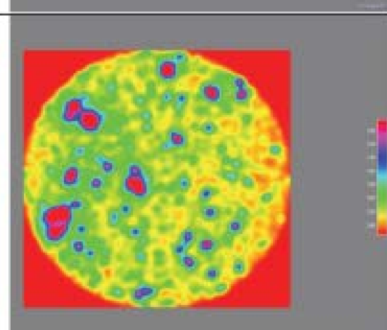
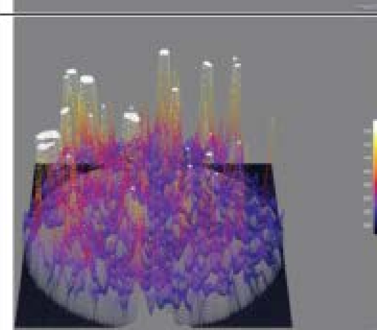
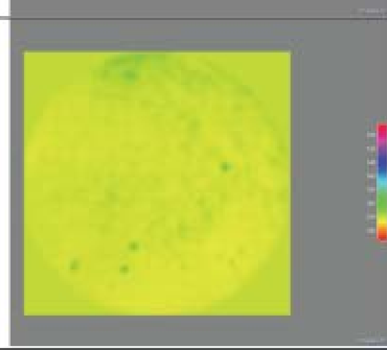
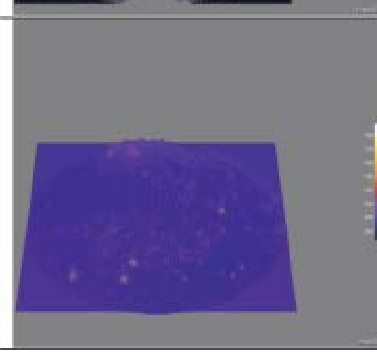
Sample Preparati on Method	Overview Image	2D Surface Plot (Fiji)	3D Surface Plot (Fiji)
Pipetted			
Slurry dispersion			
Sprinkled			
Electro-static Impactor			

Table 1. (cont.) 2-D and 3-D surface plots of all samples

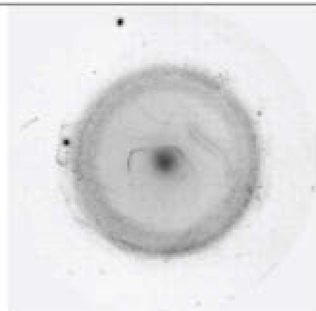
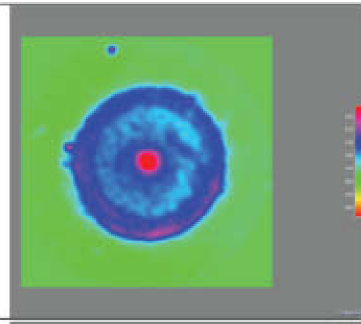
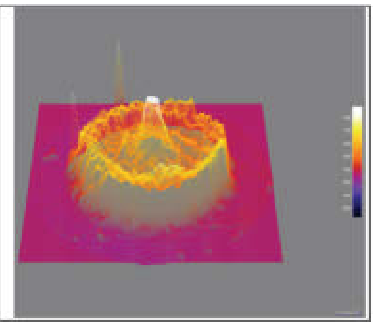
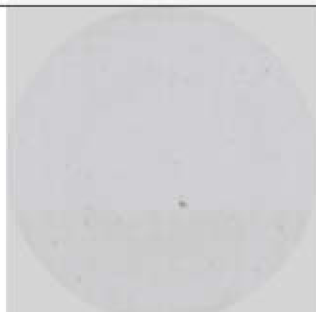
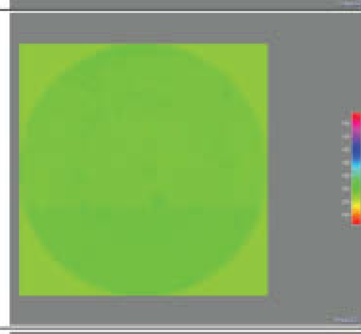
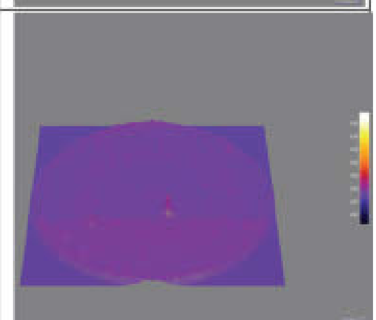
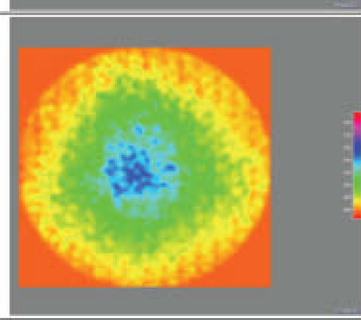
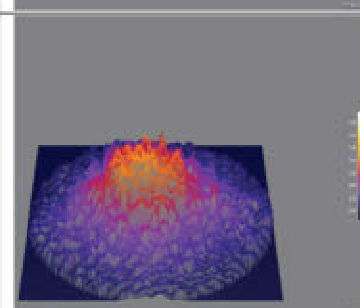
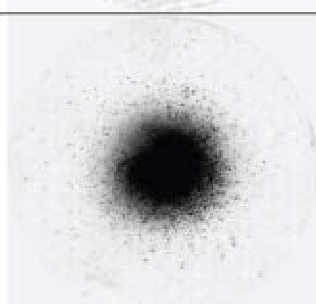
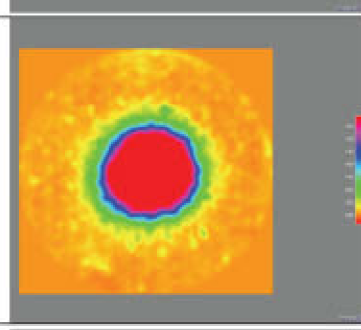
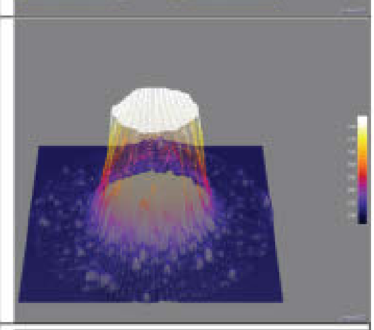
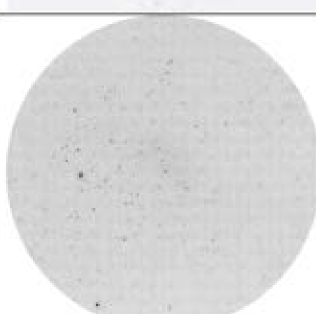
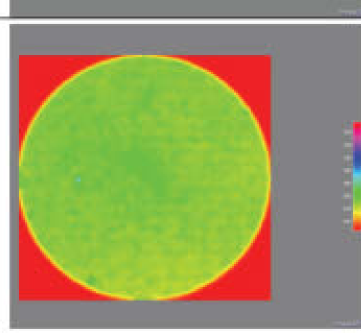
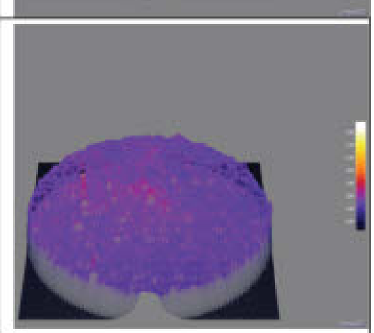
Inertial Impactor			
Inertial Impactor (blown)			
Cone at 2cm distance (1.4)			
Cylinder at 2 cm distance (1.4)			
Cone at 7cm distance (1.3)			

Table 1. (cont.) 2-D and 3-D surface plots of all samples

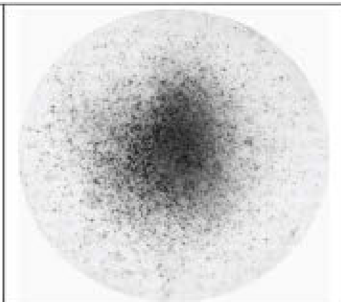
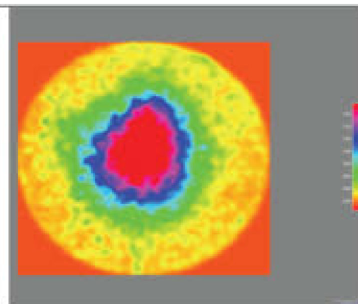
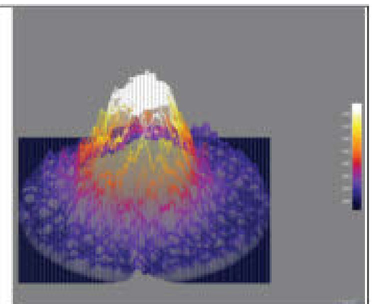
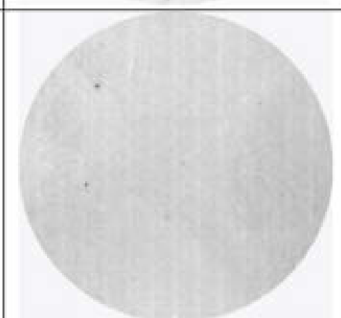
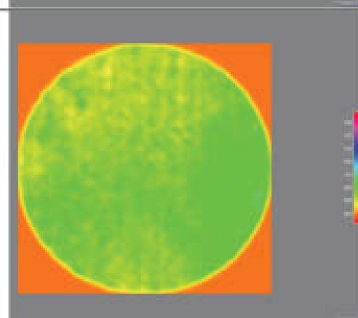
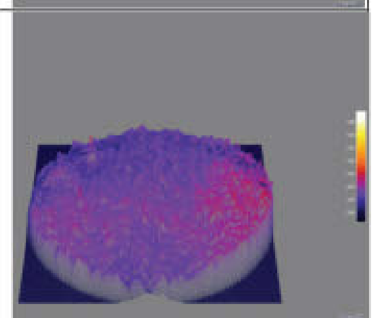
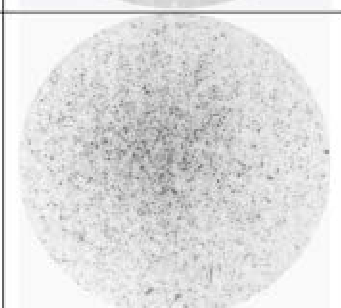
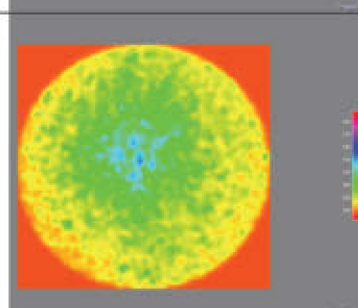
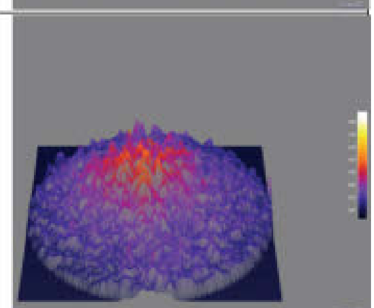
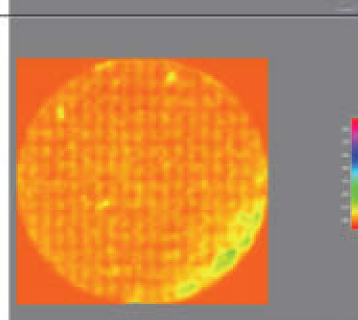
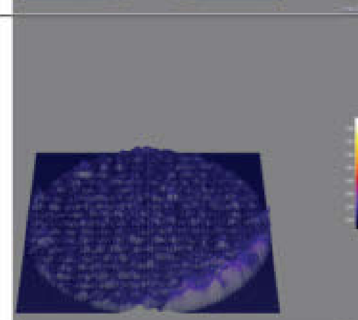
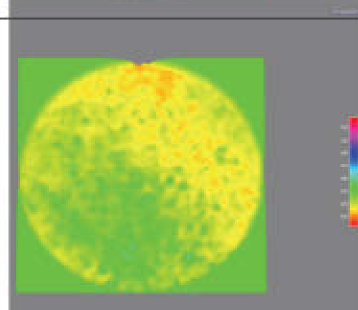
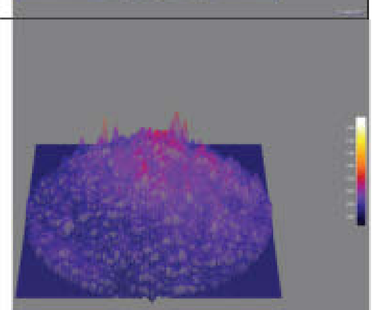
Cylinder at 7 cm distance (1.3)			
Cone at 12cm distance (1.2)			
Cylinder at 12 cm distance (1.2)			
Cone at 17cm distance (1.1)			
Cylinder at 17 cm distance (1.1)			

Figure 8. Cylinder line profiles for varying sampling distances from top of shock wave device: at bottom (dark blue, sampling distance at 17cm); step 1 (light blue, sampling distance at 12cm); step 2 (green, sampling distance at 7cm); and step 3 (orange, sampling distance at 2cm)

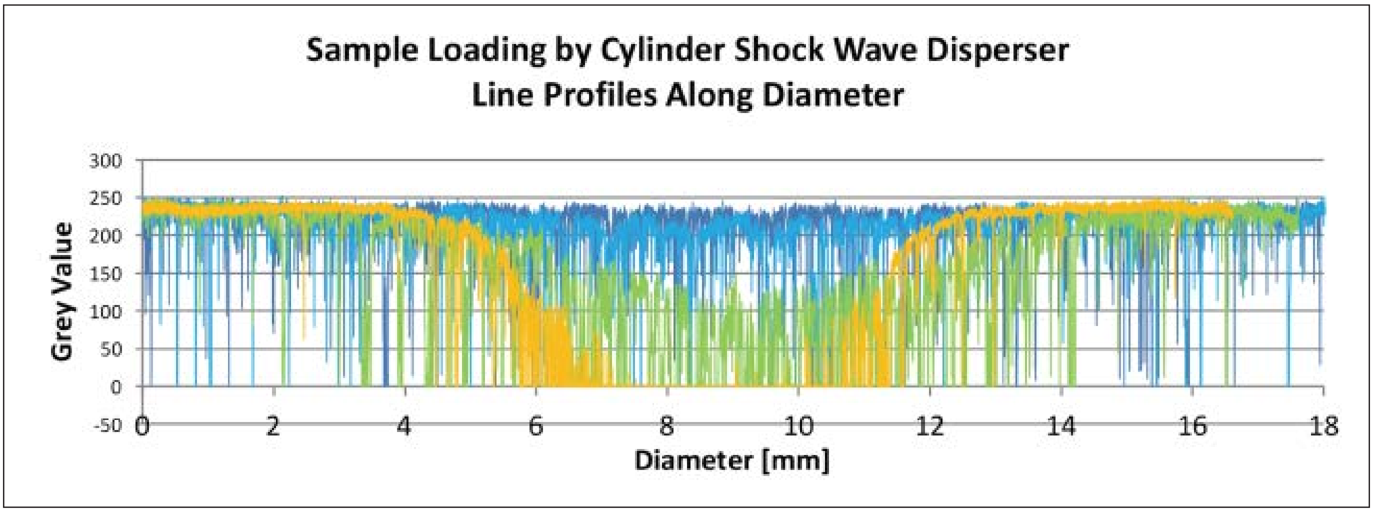
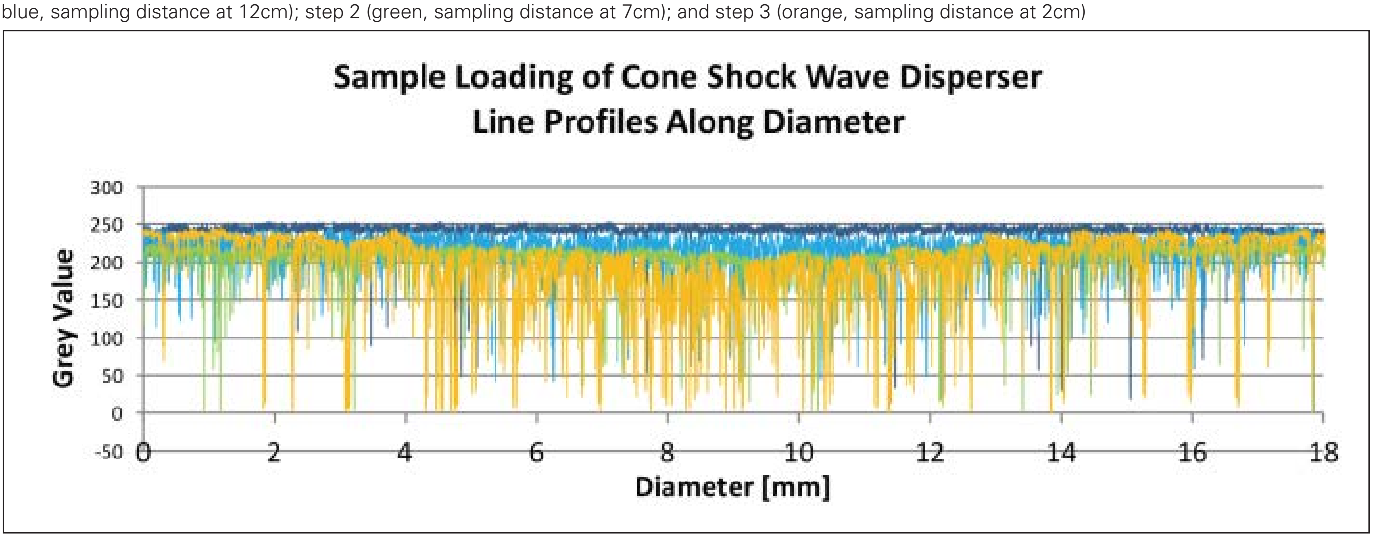


Figure 9. Cone line profiles for varying sampling distances from top of shock wave device: at bottom (dark blue, sampling distance at 17cm); step 1 (light blue, sampling distance at 12cm); step 2 (green, sampling distance at 7cm); and step 3 (orange, sampling distance at 2cm)



and cylinder driving sections behaved in a similar way, with the cone samples showing a faster decrease in axial particle loading than the cylinder samples.

Azimuthal Average

The Azimuthal Average plug-in was used to assess the radial density distribution of particle dispersion.[6] These results were an extension of the line profiling in the previous section and are displayed in the graph below as normalized integrated intensities vs. the angle at which the integration was done (-180˚ to 180˚). The integration was performed along 100 angular bins (note that the line profiles were taken along diameters). In the ideal case, for a perfectly even distribution of particles, the normalized integrated intensity along a radius will be invariant of the angle.

Concentric Circles[7]

This plug-in was used in the assessment of particle density along the perimeter of 200 circles, spread evenly around the center of the collection substrate.[7] It is a good tool for estimating the homogeneity of the distribution method at different distances from the geometrical center of the substrate. In our experiments, the shock wave disperser (at 17cm distance) with a cone head produced the most homogeneous distribution (flattest line in Figure 12).

Figure 10. Line profiles comparing the shock wave disperser (dark blue) axial loading to that of the inertial (light blue) and electrostatic impactors (light purple)

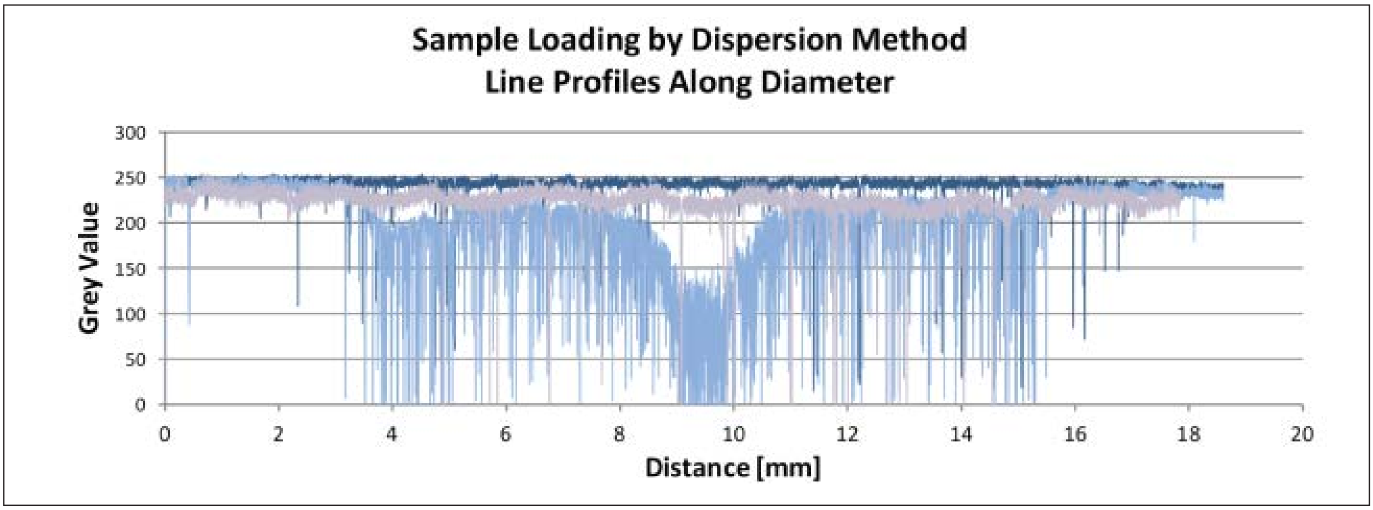
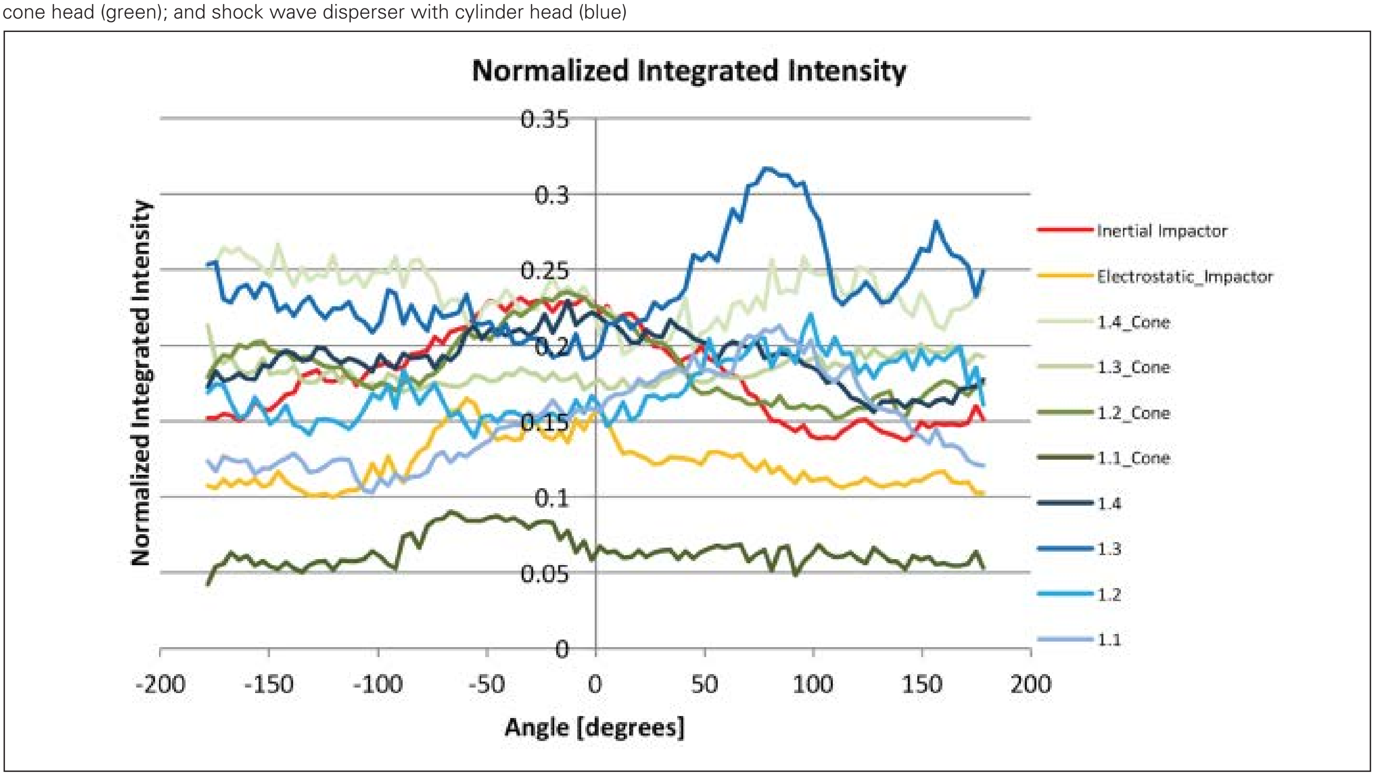


Figure 11. Normalized Integrated Intensity of particles along radii in: inertial impactor (red); electrostatic impactor (orange); shock wave disperser with cone head (green); and shock wave disperser with cylinder head (blue)



Granulometry

A more rigorous statistical method in the form of a numerical sieving tool was used: granulometry.[8] This virtual tool extracts size distribution from binary images by performing a series of morphological openings with a family of increasing particle groups and plots these into a granulometry function.[10] The function maps each structuring element to the number of image pixels removed during a single cycle. A local maximum in the pattern spectrum at a given particle size thus indicates the presence of many particles of that size. The granulometric function thus can be defined as:

$$G(k) = N(k + 1) - N(k)$$

Figure 12. Particle intensity along concentric circle at varying radii along sample: inertial impactor (red); electrostatic impactor (orange); shock wave disperser with cone head (green); and shock wave disperser with cylinder head (blue)

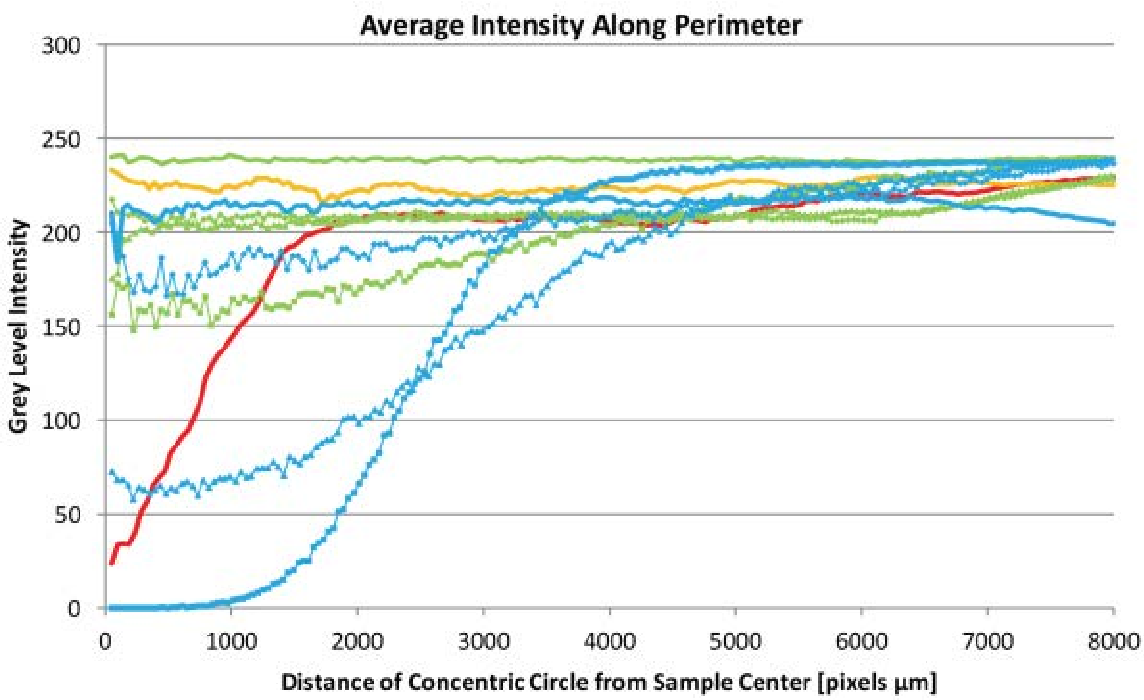
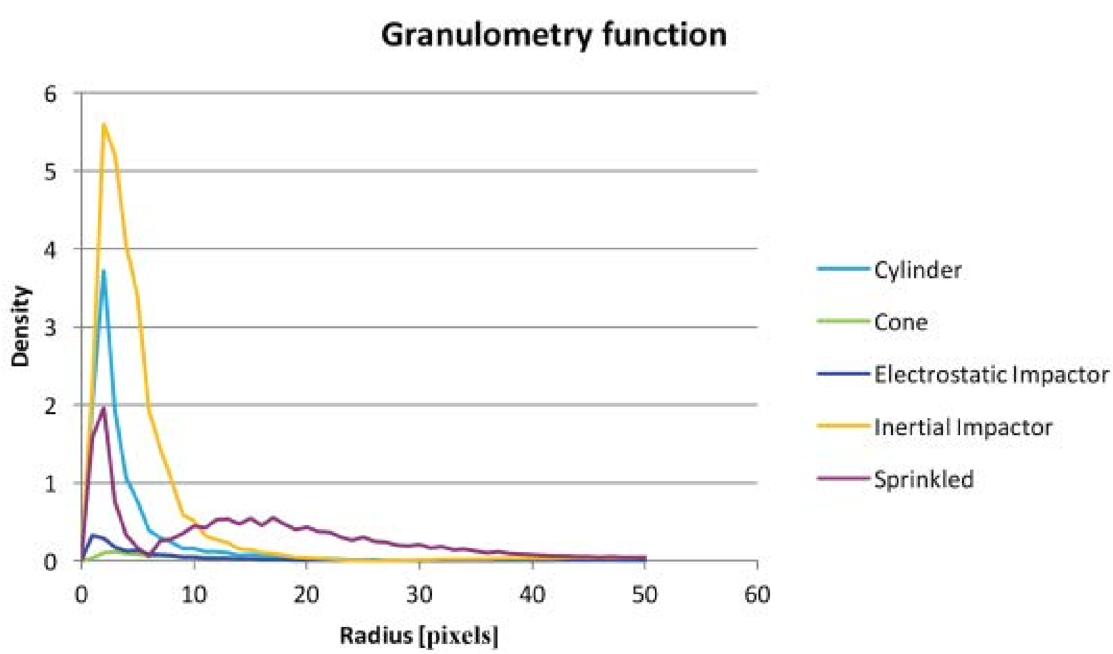


Figure 13. Granulometry function of several sampling methods. Local maxima show a preference of sampling particles of a certain size (inertial impactor method shows biggest preference towards 1-2 µm particles) or clusters. The shock wave disperser method with cone head shows the smallest preference towards particles of any given size and is thus the least biased (particles of all sizes evenly sampled). The sprinkling method has two peaks, the second of these due to particle clustering.



Where $N(k) = 1 - P_s(k)/P_s(0)$ where $P_s(k)$ is the pixel size distribution function at a certain pixel size k and $P_s(0)$ is just the pixel size distribution function of the original image[10].

To investigate the particle distribution in the small scale, SEM images processed using Fiji in the following sequence: each image was thresholded and particles identified from the background by their histogram intensity; the edges were detected after an erosion-dilation operation; and lastly, the images were segmented into either background or particle before any statistics was done. Note that the thresholding was done conservatively and some particles' sizes could have been underestimated. Also, due to the sheer number of particles in a single sample (several tens of thousands), a manual segmentation method is impractical and therefore automatic processes were used (FIJI autothresholding).

After segmentation, the areas of individual particles were calculated and are summarized in Table 2. A total of just under 40,000 particles were used in the statistical evaluation for each sample. One can see that the inertial impactor biases the dispersion towards smaller particles. One must remember that the particles are dispersed in the inertial impactor method according to their aerodynamic diameter that not always corresponds to the individual particles' physical dimensions. The shock wave disperser on the other hand produced dispersions with slightly larger averages (5.6 μm²). We believe that the latter result is closer to average soil particle sizes.

Table 2. Particle area descriptive statistics for the inertial impactor sample and the shock wave disperser method

Particle Area Descriptive Stats	Inertial Impactor	Shock Wave Disperser
Mean Particle Area Estimate	1.2±6.1 μm²	5.6±23.1 μm²
Median	0.342 μm²	1.059 μm²
Sample Variance	36.7 μm²	567.1 μm²
Minimum particle area	0.17 μm²	0.19 μm²
Maximum particle area	386.3 μm²	996.4 μm²

A total of just under 40,000 particles were used in the statistical evaluation for each sample. Figure 14 shows that the inertial impactor method favors smaller particle sizes (>60 percent of particles were smaller than 1μm2) and Figure 15 shows no particles greater than 9 μm were deposited by the inertial impactor method. This is in very good agreement with theoretical values of a cutoff particle size of ~ 9.5 μm[11]:

$$d_{p50}\sqrt{C_c} = \sqrt{\frac{9\eta D_j (Stk_{50})}{\rho_p U}} \quad (1)$$

where ρ_p is the particle density, d_{p50} is the particle diameter, U is the flow velocity, η is air viscosity, D_j is the nozzle diameter, C_c is the cutoff particle size (parameters used were $D_j = 6$ *mm* and *U = 4.51/min)*.

Figure 14. The above graph shows a slight bias for smaller particle area sizes sampled by the inertial impactor in comparison to the shock wave disperser.

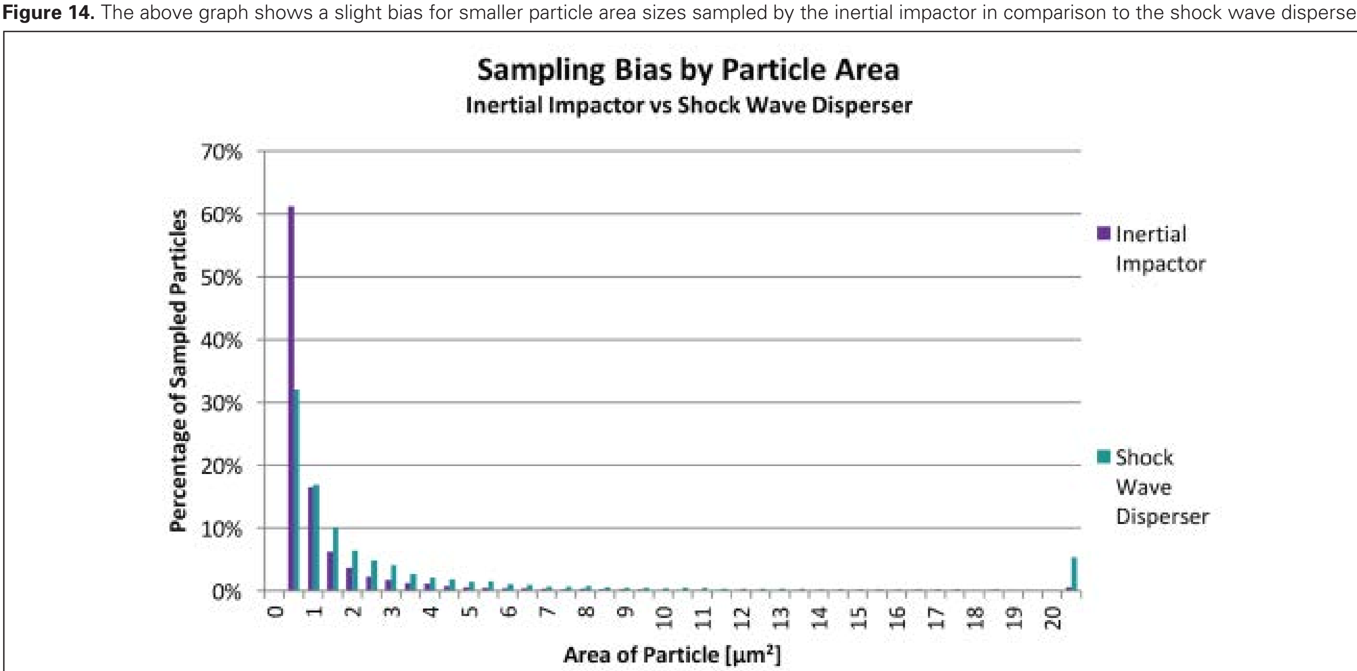


Figure 15. Empirical estimate of the cutoff value for the inertial impactor method was found at <9μm since no particles greater were found in the sample. Note that these radii were calculated from the particle area data by assuming they were spherical i.e. by 4ϖr2 = 4/3(ϖr3).

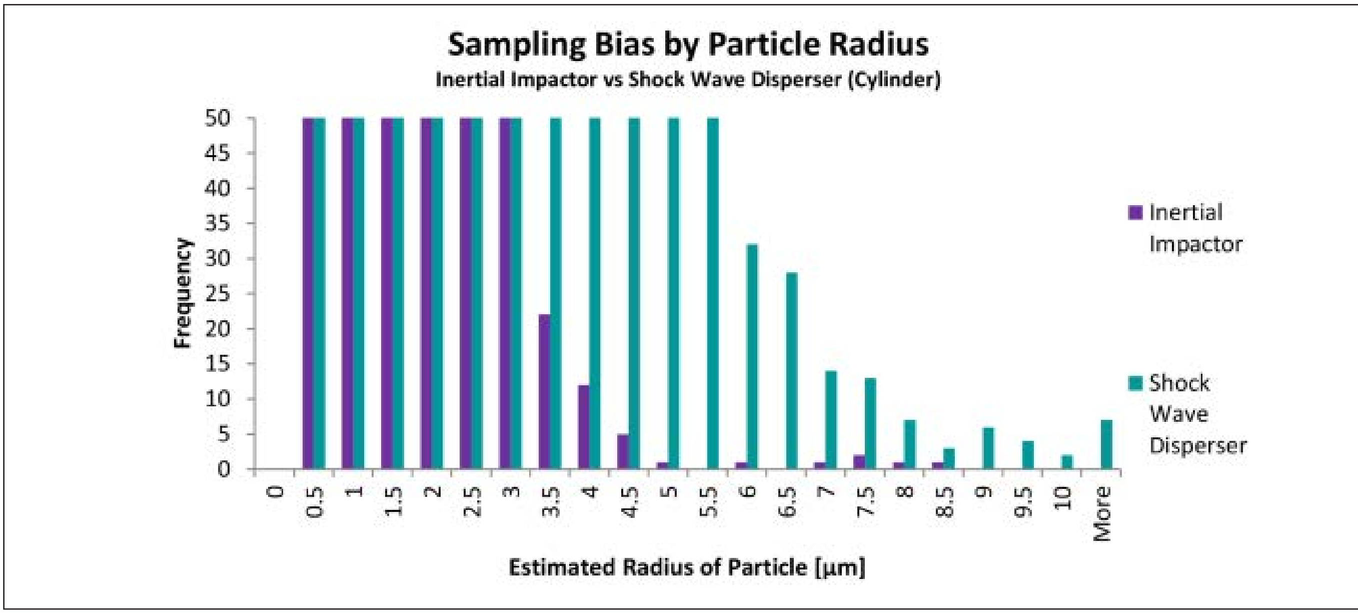
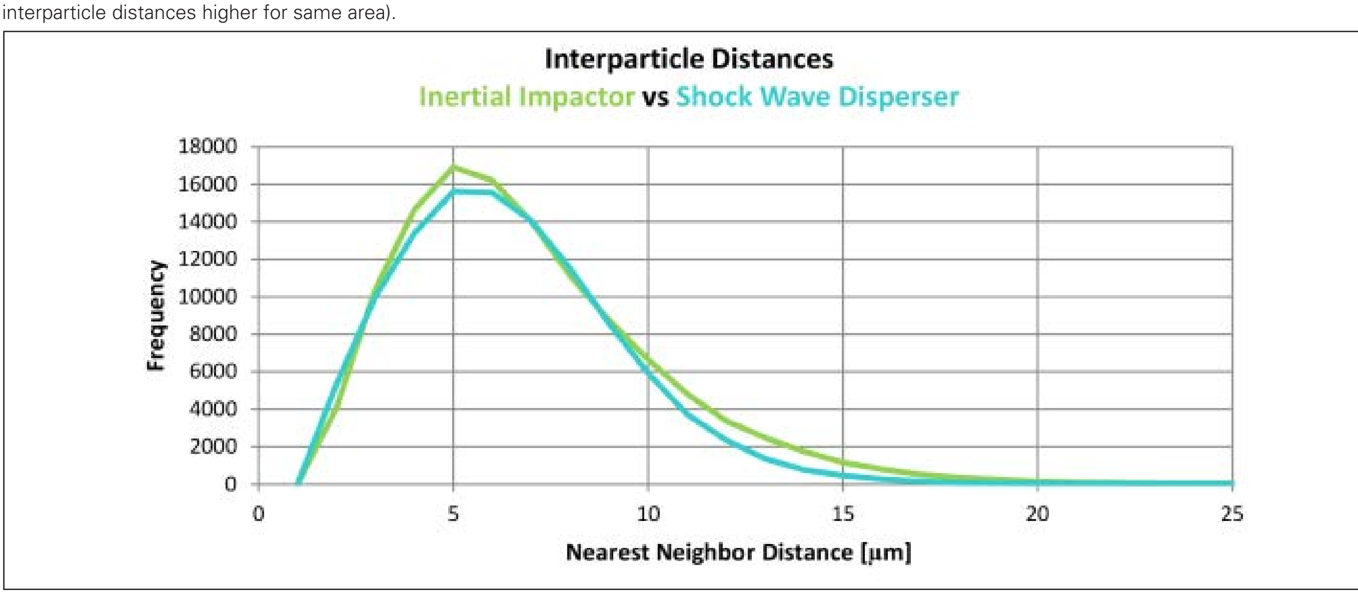


Figure 16. Normalized nearest neighbour distances for inertial impactor sample vs shock wave disperser. Note that both shock wave dispersion methods show almost exactly the same values (only cone head values are shown) and are more densily packed than the inertial impactor sample (number of interparticle distances higher for same area).



Furthermore, a plug-in for drawing the Voronoi tessellation diagram was used to estimate the inter-particle distances.[12] The algorithm estimates these by using local maxima of particles as the end-points of a single inter-particle line segment. Only distances between nearest neighbors were used in the calculation. See Figure 16 for a normalized distribution of the nearest neighbor distances. Figure 17 shows the logarithmic distribution, revealing a small deviation in inertial impactor values stemming from the outer third ring of the sample where 1 percent of the particles (172 out of 15662 total particles) occupied a third of the area (see Figure 19, top image).

Conclusion

This contribution focused on finding a practical way of determining the characteristics of existing particle dispersion methods and compared these to a new shock wave disperser device.

Figure 17. Interparticle distances by sampling method: the shoulder in the inertial impactor values suggests an area where the number of particles is smaller, thus their nearest neighbour values will deviate from expected mean values. See Figure 18 for the Voronoi triangulation plot of the inertial impactor sample and observe the outer (right) ring of the sample where in about a third of the area, there are only 172 particles located (from a total of ~16,000).

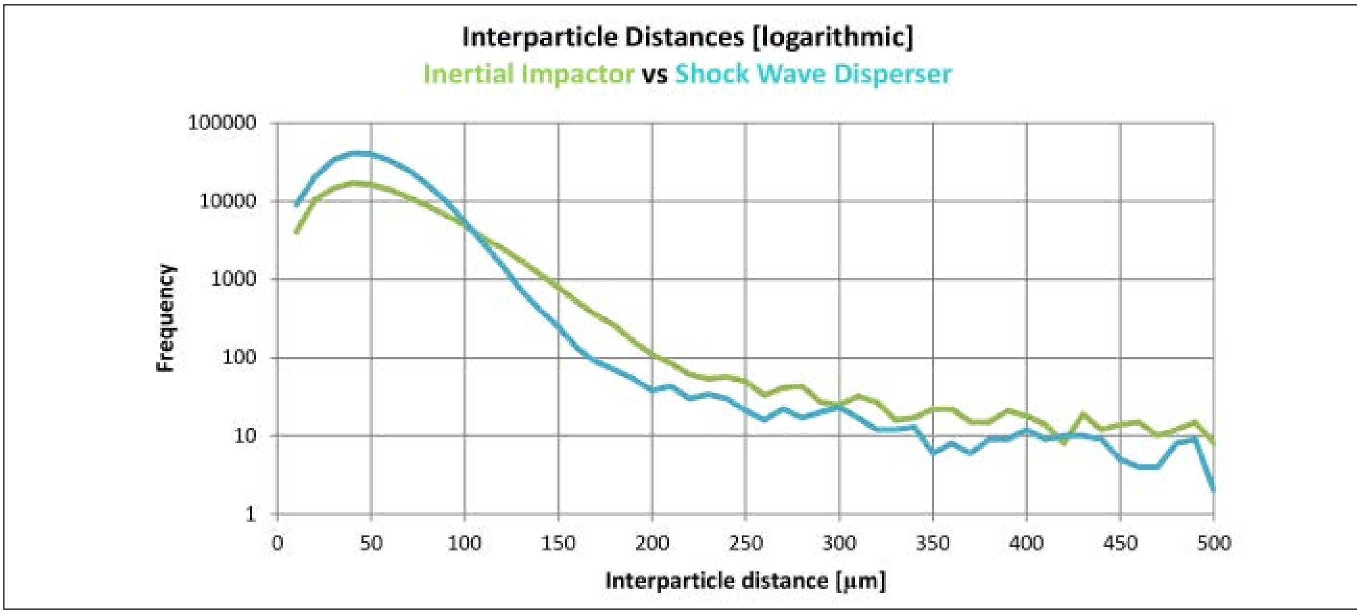


Figure 18. Delaunay Voronoi run on the shock wave disperser sample. From top to bottom: segmentation; particle area contouring; tagging of center of mass of each particle and the resulting triangulation overlay.

Figure 19. Delaunay Voronoi run on the inertial impactor sample. From top to bottom: segmentation; particle area contouring and triangulation overlay drawing (only centers of mass of particles shown). The mean separation of particles in the outer ring of the inertial impactor sample rises from 40-70µm to about 570µm.

It was found that trivial methods (sprinkling, slurry dispersion, and pipetting) suffered from the lack of reproducibility, as well as effects such as particle clustering, overlapping, and particle grouping on the edges (Marangoni effect).

Mechanical methods on the other hand produced reproducible results (as long as certain parameters were kept fixed). Several statistical tools were used to evaluate the dispersion quality, and whether each method was biased towards collecting particles of a certain size. Using Fiji software along with several plug-ins (surface plots, line profiles, azimuthal averaging, concentric circles, and granulometry), the distributions of the mechanical methods (inertial and electrostatic impactor, shock wave disperser) were found to be symmetrical around the geometrical center of the collection substrate, with little or no particle clustering. The shock wave disperser method was the method that dispersed the particles most evenly on the sample collector and showed the least bias in sampling particles based on their size (granulometry function).

In the small scale dispersion analysis, more than 60000 particles per sample were analyzed and their nearest neighbor distances plotted. It was thus confirmed that the inertial impactor biases the sampling towards the low end of the distribution, i.e. > 80 percent of the particles area sizes were between <1 to 2μm^2 and no particle was found bigger than 9μm in diameter. The shock wave dispersion method on the other hand sampled particles in a distribution that apparently matches better the intrinsic size distribution of the original material. In this case, the sampled particles ranged from < 1μm^2 to 1000μm^2 with ~ 40 percent between 1 to 2μm^2. A detailed statistical characterization of the sampled particle populations is left for future work.

Each approach has its advantages and disadvantages—the trivial sampling methods may be faster and make use of less material, but the mechanical ones enable control in the reproducibility quality and distribution of particles. The mechanical methods have issues regarding potential contamination of the laboratory environment and cross-contamination between samples. Future work will involve miniaturization of the shock wave disperser device, as well as methods for controlling contamination.

References

1. "CADFEM," [Online]. Available: http://cadfem.en.softonic.com/.
2. IAEA, "Report on Intercomparison IAEA/Soil7 of the Determination of Trace Elements in Soil," IAEA, Vienna, 1984.
3. J. Schindelin and I. &. F. E. e. a. Arganda-Carreras, Fiji: An Open-source Platform for Biological-image Analysis, *Nature Methods 9(7),* vol. 9, no. 7, pp. 676-682, 2012.
4. K. Barthel. Interactive 3D Surface Plot, 2008. [Online]. Available: http://imagej.net/plugins/surface-plot-3d.html.
5. W. Rasband. Dynamic Profiler. 2003. [Online]. Available: http://rsb.info.nih.gov/ij/plugins/dynamic-profiler.html.
6. P. Carl. Azimuthal Average. 2007. [Online]. Available: http://rsb.info.nih.gov/ij/plugins/azimuthal-average.html.
7. R. Wayne. Concentric Circles. 2007. [Online]. Available: http://rsb.info.nih.gov/ij/plugins/concentric-circles.html.
8. D. Prodanov. Granulometric Filtering. 2005. [Online]. Available: http://fiji.sc/Granulometric_Filtering.
9. J. Schindelin and L. P. Chew. Delaunay Voronoi. 2006. [Online]. Available: http://fiji.sc/Delaunay_Voronoi.
10. G. Matheron, *Randoms Sets and Integral Equation,* New York: Wiley, 1978.
11. C.-Y. Wu. Aerosol Transport. University of Florida, [Online]. Available: http://aerosol.ees.ufl.edu/aerosol_trans/section09_d.html.
12. J. Schindelin and P. Chew. Delaunay Voronoi. 2006. [Online]. Available: http://fiji.sc/Delaunay_Voronoi.

Keywords:

Safeguards, sample preparation, optical microscopy, SEM, shock wave disperser, inertial impactor, electrostatic impactor, Fiji.

Sensitivity Analysis of Neutron Multiplicity Counting Statistics Using First Order Perturbation Theory for a Subcritical Plutonium Benchmark

Sean O'Brien, John Mattingly, and Dmitriy Anistratov
North Carolina State University, Raleigh, North Carolina USA

Abstract

Neutron multiplicity counting measurements enable nondestructive detection of special nuclear material. It is important to estimate the uncertainty and sensitivity of measured and simulated detector responses of the neutron multiplicity counting distribution. These uncertainties arise from the physical construction of the experiment, from uncertainties in the transport parameters, and from counting uncertainties. In particular, in subcritical experiments the detector response is geometrically sensitive to the fission neutron yield distribution. The detector response is an integral quantity and therefore perturbation theory is used to perform a complete sensitivity analysis and uncertainty quantification (SA/UQ) on the moments of the neutron multiplicity counting distribution. Current SA/UQ methods have only existed for the mean of the distribution. We apply perturbation theory to compute the sensitivity of neutron multiplicity counting moments to arbitrarily high order. Each moment is determined by solving an adjoint transport equation with a source term that is a function of the adjoint solutions for lower order moments. This enables moments of arbitrarily high order to be sequentially determined and shows that each moment is sensitive to the uncertainties of all lower order moments. We derive SA/UQ closing equations that are a function of the forward flux and lower order moment adjoint fluxes. We validate our calculations for the first two moments by comparison with multiplicity measurements of a subcritical plutonium metal sphere. We compute the first four moments of the multiplicity distribution and rank the sensitivity of the moments to nuclear data parameters. This work will enable a new method to adjust the evaluated values of nuclear parameters using subcritical neutron multiplicity counting experiments. A transport-theory based model of neutron multiplicity moments uses fewer approximations than point-reactor based models, enabling a more detailed sensitivity and uncertainty analysis of subcritical multiplicity counting measurements of fissionable material.

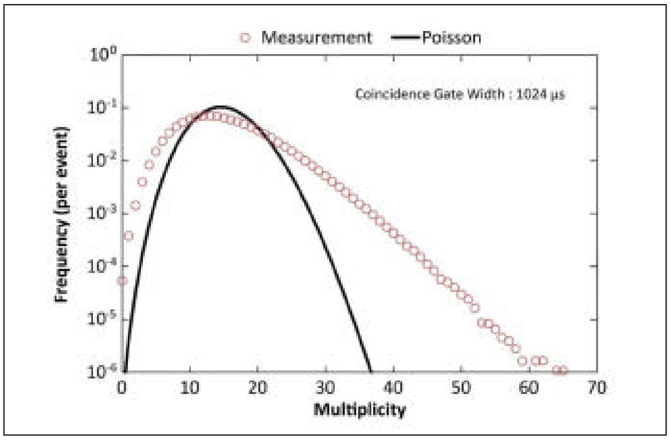
Introduction

To accurately characterize a subcritical neutron multiplying system, such as the plutonium sphere considered in this work, we must account for the higher order moments, beyond the mean, of the neutron multiplicity counting distribution. Non-multiplying systems are characterized by Poisson statistics, where all higher order moments are explicit functions of the mean, as all neutron interactions are independent. Neutron multiplying systems introduce dependencies between events due to fission chain-reactions and introduce correlations between stages in fission chains.[1]

We count the number of coincident neutrons during a gate to construct a neutron multiplicity counting distribution,[2] Figure 1. The deviation from the Poisson distribution is evident in the broadening of the multiplying system distribution as a result of variations in the neutron population from fission chains of differing length. Knowledge of the moments of the distribution enables us to characterize the kinetic parameters of the fissile system via nondestructive assay through several integral quantities: neutron source strength, multiplication, and generation time.[3, 4]

For a complete analysis we require knowledge of the associated sensitivities and uncertainties in our measurements and simulations, that arise from uncertainties in the nuclear data, physical construction of the experiment, and from counting uncertainties. We calculate the moments of the distribution by considering moments of the stochastic neutron transport equation (STE), which are inner products of deterministic forward/adjoint fixed source transport problems.[5, 6] As the moments of the counting distribution are inner products we use first order perturbation theory to facilitate SA/UQ on the moments to arbitrarily high order. To close our SA/UQ system we develop contribution equations that couple the sensitivities between counting moments. All problems solved in this work are implementable in any forward/adjoint deterministic transport code capable of solving fixed source subcritical problems, such as PARTISN.[7, 8]

Figure 1. Poisson distribution compared to multiplicity distribution measured from a subcritical plutonium sphere, [3]. Fission chains cause a deviation from Poisson statistics.



We use our new SA/UQ methodology on the moments of the neutron multiplicity counting distribution for the BeRP ball (Beryllium Reflected Plutonium). The BeRP ball is a subcritical sphere of weapons grade plutonium.[9] We validate our calculations with experimental measurements of the mean count rate and excess relative variance (Feynman-Y).[10] Finally, we generate the relative sensitivity coefficients for the mean and second moment of the counting distribution and explore the range of validity of first order perturbations for the mean and Feynman-Y.

Moment and Contribution Equations

The moments of the neutron multiplicity counting distribution are arrived at by considering inner products of solutions derived from the moments of the STE, developed by Pal[6] and Bell[11] in terms of factorial moments. The qth order factorial moment is defined as,

$$\overline{n(n-1)\dots(n-q+1)} = \sum_{n=q-1}^{\infty} n(n-1)\dots(n-q+1)p_n \tag{1}$$

where the over-line denotes the expected value, and *pn* is the probability associated with n-coincident neutrons. The moment equations are a set of downwardly coupled linear adjoint and forward Boltzmann transport equations. Each moment possess a unique fixed source that is a function of lower order moment solutions. The SA/UQ closing equations, that couple the sensitivity between moments, are forward transport equations whose fixed source is a convolution of lower order moment forward and adjoint solutions.

We present the highlights of our derivations for the mean and second moments only, in previous work,[12] we explicitly derived the moment and contribution equations. The mean count rate, *R1*, is obtained by the standard inner product definition,

$$R_1 = \int_V d^3\vec{r} \int_0^\infty dE \int_{4\pi} d\Omega \sigma_d \psi = \langle \sigma_d, \psi \rangle \tag{2}$$

where Ψ is the usual forward flux and $\sigma\, d$ is the detector macroscopic cross-section (effectively a detector response function with units of cm^{-1}). Using the adjoint equality, $\langle L^\dagger \psi^\dagger, \psi \rangle = \langle \psi^\dagger, L\psi \rangle$, where $L^\dagger$ and L are the adjoint and forward transport operators, respectively, we can express the mean count rate as

$$R_1 = \langle \sigma_d, \psi \rangle = \left\langle \psi_1^\dagger, Q \right\rangle \tag{3}$$

where Q is the usual neutron source term in the Boltzmann transport equation and $\psi_1^\dagger$ is the solution of Eq. 4.

$$L^\dagger \psi_1^\dagger = \sigma_d = Q_1^\dagger \tag{4}$$

By considering the adjoint we are able to circumvent derivatives of the forward flux with respect to the transport parameters when constructing the sensitivities of the mean.[13] The mean adjoint flux represents the phase-space map of potential neutron births to contributions to the mean count rate, *R1*. The adjoint is essential to SA/UQ as the set of transport parameters, $\vec{\alpha}$,is typically on the order of thousands, consisting of densities, energy grouped cross-sections and other data: fission yield and spectrum distributions, decay rates, etc. Using the adjoint we arrive at a calculable expression (i.e., on that contains no flux derivatives) of the first order sensitivity of the mean to our parameters, Equation 5.

$$\frac{\partial R_1}{\partial \vec{\alpha}} = \left\langle \frac{\partial \sigma_d}{\partial \vec{\alpha}}, \psi \right\rangle + \left\langle \psi_1^\dagger, \frac{\partial Q}{\partial \vec{\alpha}} - \frac{\partial L}{\partial \vec{\alpha}} \psi \right\rangle \tag{5}$$

The second moment of the count rate, R_2, is given by Equation 6,

$$R_2 = \left\langle Q_2^\dagger, \psi \right\rangle = \left\langle \psi_2^\dagger, Q \right\rangle \tag{6}$$

and is the solution of Eq. 7.

$$\begin{aligned} L^\dagger \psi_2^\dagger &= \overline{\nu(\nu-1)}\sigma_f \left(\int \int dE' d\Omega' \frac{\chi}{4\pi} \psi_1^\dagger \right)^2 \\ &= \overline{\nu(\nu-1)}\sigma_f I_1^2 = Q_2^\dagger \end{aligned} \tag{7}$$

where,

$$I_1 = \int\int dE' d\Omega' \frac{\chi}{4\pi}\psi_1^\dagger \tag{8}$$

is the spatial importance (assuming all fission neutrons are born with the same spectrum) of an induced fission at ~r to the response, which appears as a square, since neutron doubles are formed by pairs of singles, and $\overline{\nu(\nu-1)} = \sum_{j=1}^{N} j(j-1)p_\nu(j)$.[12]

The first order sensitivity of the second moment contains derivatives of the forward flux and mean adjoint. The derivatives of the forward flux are avoided by the mean adjoint, as in Equation 5. The mean adjoint flux derivatives are circumvented by a contributon equation, Equation 9.

$$L\Phi_2 = \left(\int\int dE'd\Omega'\frac{\chi}{4\pi}\psi_1^\dagger\right)\frac{\chi}{4\pi}\int\int dE'd\Omega'\overline{\nu(\nu-1)}\sigma_f\psi = Q_2 \tag{9}$$

The contributon flux, Φ_2, is the forward flux of neutron doubles that contribute to the second moment. This is apparent in the source term, Q_2, where we have the production of fission doubles weighted by their importance. We can now write the first order sensitivity of the second moment, Equation 10.

$$\frac{\partial R_2}{\partial\vec{\alpha}} = \left\langle \psi_2^\dagger, \frac{\partial Q}{\partial \vec{\alpha}} - \frac{\partial L}{\partial\vec{\alpha}}\psi\right\rangle + \left\langle \frac{\partial Q_2^\dagger}{\partial\vec{\beta}}\frac{\partial\vec{\beta}}{\partial\vec{\alpha}},\psi\right\rangle + 2\left\langle \frac{\partial Q_1^\dagger}{\partial\vec{\alpha}} - \frac{\partial L^\dagger}{\partial\vec{\alpha}}\psi_1^\dagger, \Phi_2\right\rangle \tag{10}$$

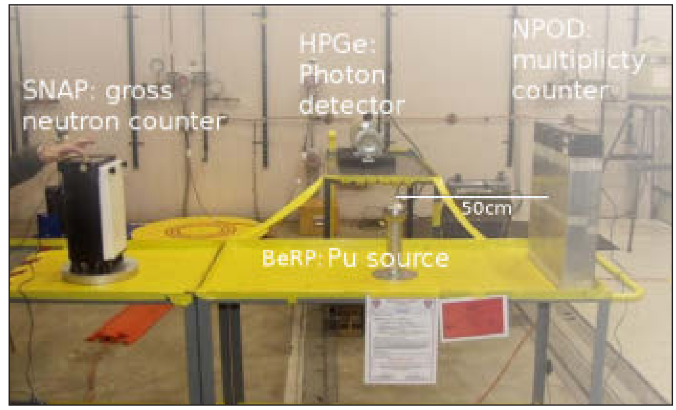
where we have defined a subset of parameters, $\vec{\beta}$, = $\left(\sigma_f, \chi, \overline{\nu(\nu-1)}, \dots, \overline{\nu(\nu-1)\dots(\nu-\nu_{max})}\right)$as the contribution terms are only required for mean adjoint flux derivative terms.[12] With the moments and their sensitivities defined we turn to some computational results.

Numerical Results

We validated our model using experimental data of the bare BeRP ball, a 4.4 kg sphere of alpha-phase weapons grade plutonium metal with the NPOD detector, which contains an array of SA/UQ of Neutron Multiplicity Statistics 50cm ^{3}He proportional counters.[9] The subcritical plutonium source has a radius of 3.794 cm, and consists of 94 percent ^{239}Pu (multiplying medium) and 6 percent ^{240}Pu (spontaneous fission source) by mass fraction.[9] The experimental setup is depicted in Figure 2.

In Reference 12, we validated our model by computing k-effective (k_{mcnp} = 0:7768 and k_{calc} = 0:7667[14], the mean count

Figure 2. Experimental arrangement at Nevada Test Site



rate ($R_{1;exp}$ = 8:284x10³ cps and $R_{1;calc}$ = 8:297x10³ cps[15]), and relative excess variance, Equation 11, where μ is the mean and σ^2 is the variance, (Y_{exp} = 0:33 and Ycalc = 0:34[3]), which agreed well with experiment.

$$Y = \frac{\sigma^2}{\mu} - 1 = \frac{R_2}{R_1} \tag{11}$$

We approximated the detector response function, σd, as an efficiency, abs(E), on the boundary of the sphere.[3] The absolute detector efficiency is the product of the intrinsic detector efficiency with the solid angle, $\epsilon_{abs} = \frac{\Omega}{4\pi}\epsilon_{int}$.

We compute the response by convolving the detector response function, Figure 3, with the neutron leakage current, $\vec{j}$, such that the detector response function is treated as, Equation 12,

$$\sigma_d(\vec{r}, E, \vec{\Omega}) = \hat{n}\cdot\vec{\Omega}\delta(\vec{r}\varepsilon\partial V)\epsilon_{abs}(E) \tag{12}$$

where ∂V is the source boundary surface and $\hat{n}$ is the surface normal vector. As $\vec{j}$ = $\vec{\Omega}\psi$, the mean count rate is calculated as,

$$R_1 = \int_{\vec{r}\varepsilon\partial V} d\vec{r}\int dE\int_{\hat{n}\cdot\vec{\Omega}>0} d\Omega\epsilon(E)\hat{n}\cdot\vec{j}(\vec{r}, E, \vec{\Omega}) \tag{13}$$

and similarly for the second moment, *R2*. Since the publication of Reference 12, we discovered that our transport solutions were not fully converged with our chosen spatial and S_N discretizations. We performed a space-angle convergence test for the mean and Feynman-Y, Equation 11, the relative excess variance, in Figure 4. Using the convergence data, we performed an Aitken extrapolation and observed a reduction in the mean count rate, R_1, from 8; 300 cps to 8; 000 cps. A reduction in the

Feynman-Y was observed as well, from 0:33 to 0:30. While our seemingly fortuitous, though inaccurate, choice of discretizations agreed very well with experiment, it did not support previous findings that for ^{239}Pu was in error[16]. Our converged results serve to substantiate the prior findings concerning the average fission yield for ^{239}Pu.

Relative Sensitivity Coefficients

Using the first order sensitivities of the moments of the count rate we can construct relative sensitivity coefficients, $S_{\vec{\alpha}}^{R_q}$, for each moment of order q, defined as Equation 14 for each parameter n.

$$S_{\alpha_n}^{R_q} = \frac{\alpha_n}{R_q}\frac{\partial R_q}{\partial \alpha_n} \tag{14}$$

We present several of the most influential parameters in group collapsed form, where we multiply the integrated group-wise sensitivity coefficients by the energy average of the parameter divided by the count rate moment. The value of a relative sensitivity coefficient is a measure of the percentage change in the observable, count rate moment, given a 1 percent change in the parameter. E.g., for $S = 4$, a 4 percent change is observed.

The mean count rate is most sensitive to fission parameters for ^{239}Pu, σ_f and ν^{-}, as seen in Figure 5. This sensitivity is expected as it is the major source of neutrons as the bare BeRP ball has a neutron multiplication factor of M = 4:4.[9] The mean is also sensitive to the scattering cross-section as fission neutrons are born fast and down scattering would enable more fissions where the fission cross-section is larger (thermal domain).

The second moment is dramatically sensitive to the fission parameters, as seen in Figure 5. This markedly large sensitivity arises from the coupling between the mean and second moment, recall that the second moment adjoint source term is a function of the mean adjoint flux squared, Equation 7. This causes a parameter perturbation/uncertainty in the mean to be amplified in the second moment.

Figure 3. Intrinsic detector efficiency $\sigma_d / \varepsilon\Omega$

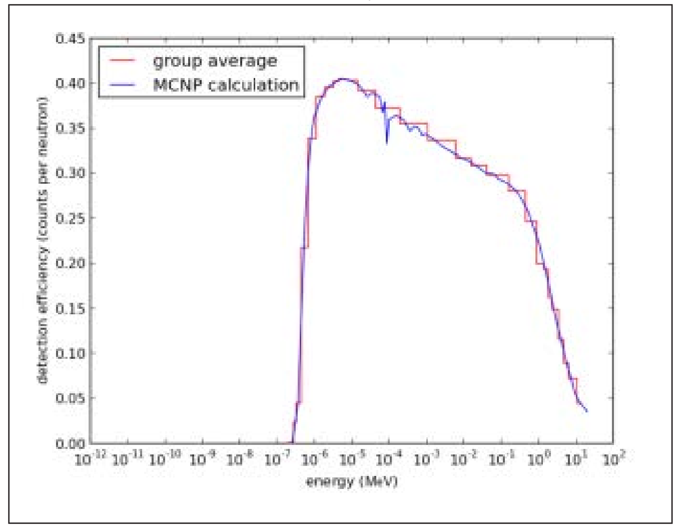


Figure 4. Space-angle convergence test for R1 and Y (relative excess variance), where 2N is number of uniform spatial mesh cells and SN is the order of angular quadrature. The mean response is calculated using 12.

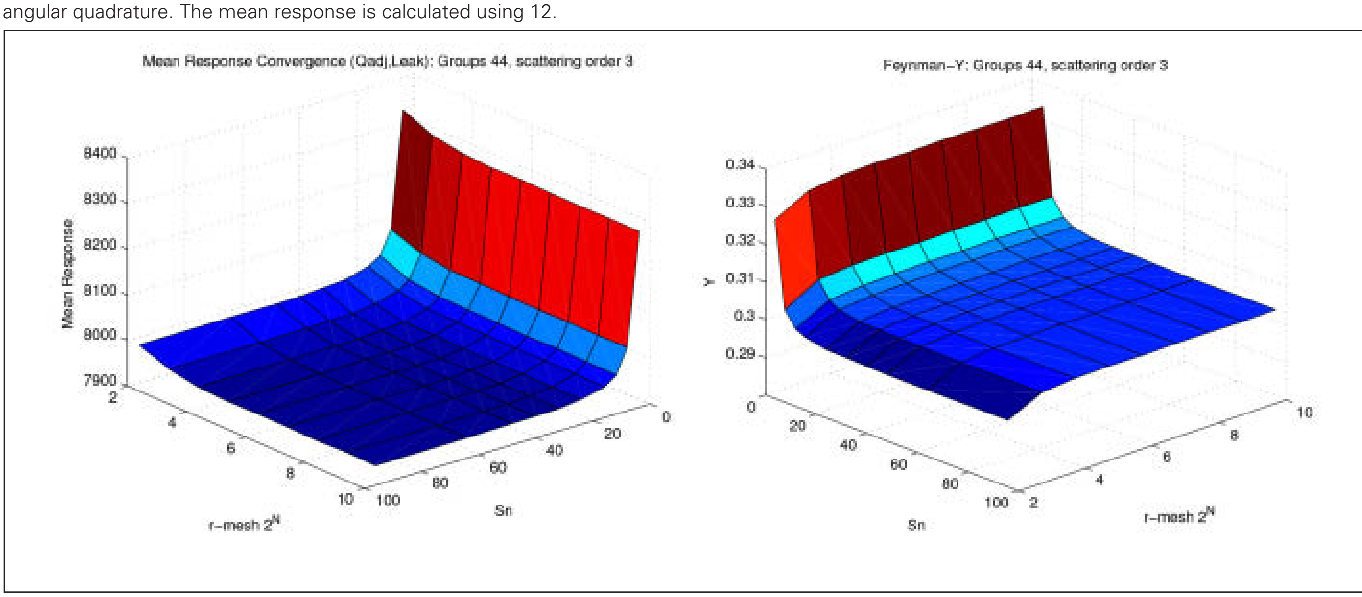


Figure 5. Group collapsed relative sensitivity coefficients of the mean count rate, R1, and second moment count rate, R2

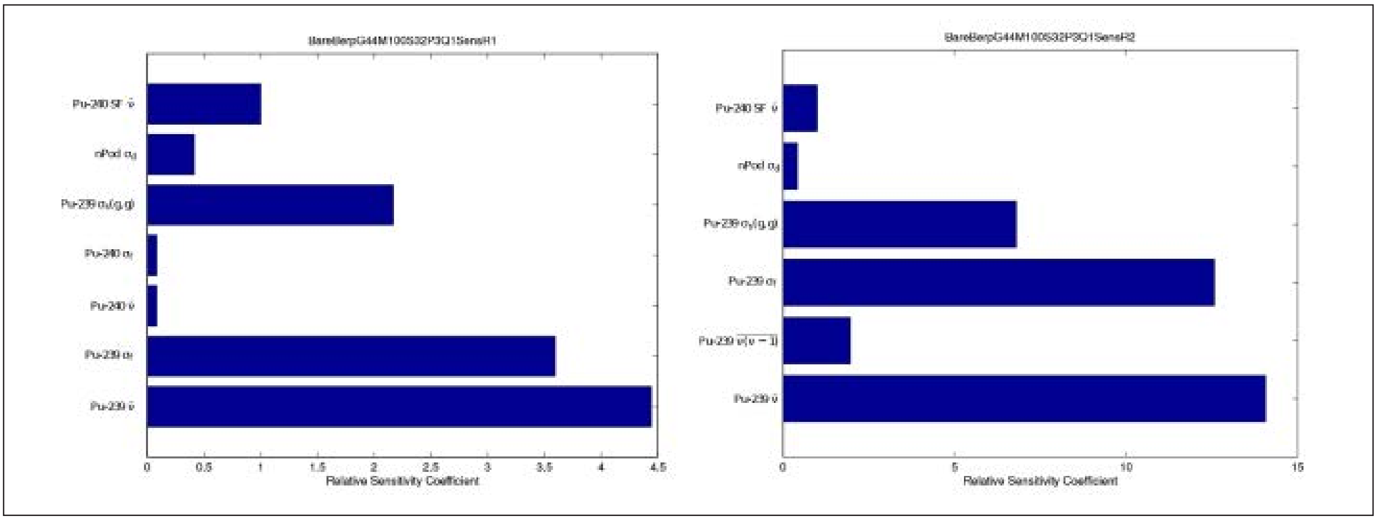
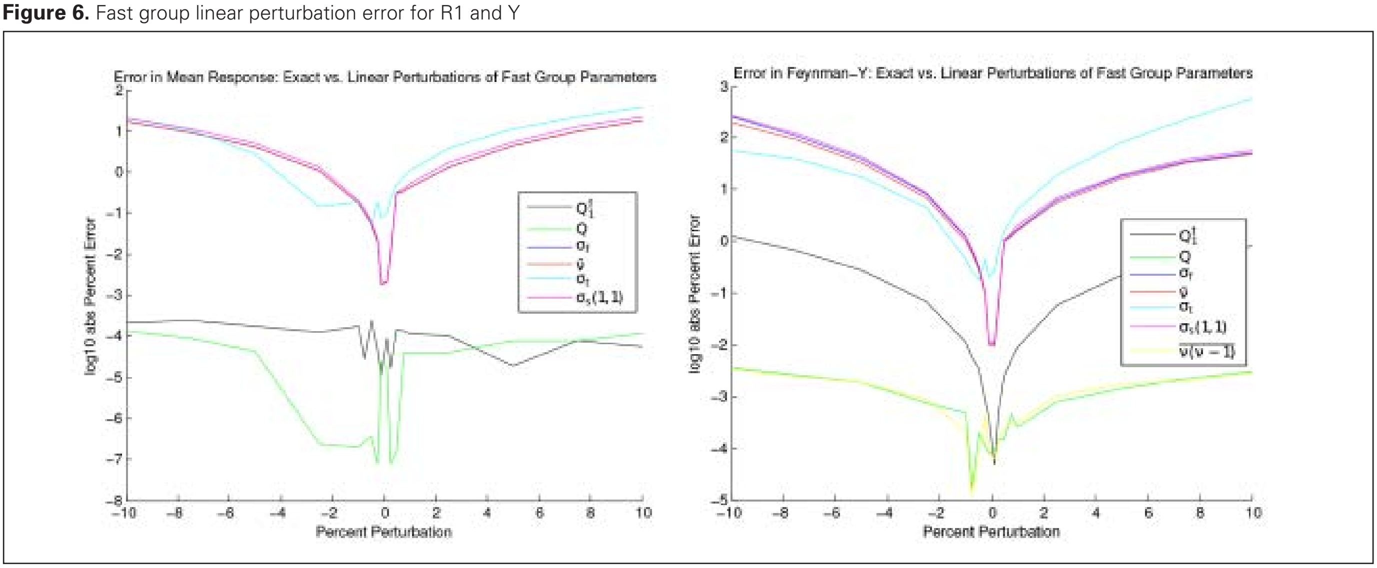


Figure 6. Fast group linear perturbation error for R1 and Y



We used a reaction rate collapsed two-group problem to investigate the range of validity of the first order sensitivity approximation for the mean and the Feynman-Y. First order perturbation theory can be shown to be invalid when the change in the response is larger than the perturbation. In some problems, the assumption inherent to first order perturbation theory that the first order Taylor series truncation is an accurate representation of sensitivity (i.e., responses change linearly with perturbations) can be invalid. Other researchers, such as Abdel-Khalik's generalized perturbation theory,[17, 18] have developed higher order sensitivity analysis that do not assume the first order Taylor series truncation is valid.

Cross sections were collapsed from 44-groups using the flux spectrum, and moments of $P\nu$ were collapsed using the fission rate spectrum ($\sigma_f \Psi$). We independently perturbed each parameter and found the relative error between the linear approximation, using the sensitivity coefficients, and explicit transport solves using the perturbed parameters. In Figure 6 are the fast group linear perturbation errors, where a 1 on the vertical axis corresponds to a 10 percent error. The thermal group is negligible as there is minimal thermalization in plutonium metal. The error in the mean is acceptable over a wide range of perturbations. The Feynman-Y error is manageable for small perturbations but drastically increases for larger perturbations, particularly for $\bar{\nu}$ and σ_f.

Conclusions and Future Work

In summary, we developed a new method of performing SA/UQ on the count rate moments of the neutron multiplicity counting distribution. We have developed the moment equations up to tenth order and the SA/UQ contribution closing equations to fifth order, for induced and spontaneous fission contributions. All equations required of this work (forward, adjoint and contribution) can be solved by any forward/adjoint fixed source deterministic transport code, enabling easy implementation into existing codes. The equations are only coupled in the downward direction permitting one to sequentially solve up to the desired order moment.

We found that our converged count rate moments substantiate earlier findings that for ^{239}Pu is incorrect.[16] The relative sensitivity coefficients revealed a strong coupling between the first and second moments, expressed as large coefficients in the fission data. Present work is focused on explicitly verifying the range of validity of the first order sensitivity approximation for the mean and second moment using a more refined group structure. We will improve these calculations by using HPC resources using a more refined group structure, beyond the 44-groups considered here. With sensitivity coefficients we will perform UQ by propagating the uncertainty in the parameters SA/UQ of Neutron Multiplicity Statistics to yield the uncertainty in the count rate moments by,

$$C_{R_q} = \frac{\partial R_q}{\partial \vec{\alpha}} C_\alpha \left(\frac{\partial R_q}{\partial \vec{\alpha}} \right)^T \tag{15}$$

where CRq is the uncertainty in the qth moment, and C is the model parameter covariance matrix.[16] Finally, we will explore the impact of reflected plutonium spheres, beyond the current bare BeRP ball studies.

Acknowledgement

The information presented in this paper is based upon work supported by the Department of Energy National Nuclear Security Administration under Award Number(s) DE-NA0002576.

Key Words

neutron multiplicity, sensitivity analysis and uncertainty quantification

References

1. Prasad, M. K., and N. J. Snyderman. 2012. Statistical Theory of Fission Chains and Generalized Poisson Neutron Counting Distributions, *Nuclear Science and Engineering,* 172, pp. 300–326.
2. Ensslin, N., et al. 1998. Application Guide to Neutron Multiplicity Counting, Los Alamos National Laboratory, LA-13422-M.
3. Mattingly, J. 2012. Computation of Neutron Multiplicity Statistics Using Deterministic Transport, *IEEE Transactions* on Nuclear Science, 59, 2.
4. Cifarelli, D., and W. Hage. 1986. Models for a Three-Parameter Analysis of Neutron Signal Correlation Measurements for Fissile Material Assay, *Nuclear Instruments and Methods in Physics Research,* A251, pp. 550–563.
5. Munoz-Cobo, J.-L., et al. 1987. Stochatic Neutron Transport Theory, *Nuclear Science and Engineering*, 95, pp. 83–105.
6. Pal, L. 1958. *On the Theory of Stochastic Processes in Nuclear Reactors,* Nuovo Cimento, 7, pp. 25–42.
7. Fichtl, E. D., and R. S. Baker. 2013. Computing the Moments of the Neutron Population using Deterministic Transport, *Proceedings of ANS M&C*, Sun Valley, Idaho USA.
8. Alcouffe, R., et al. 2008. PARTISN: A Time-Dependent, Parallel Neutral Particle Transport Code System, LA-UR-08-07258.
9. Mattingly, J. 2009. Polyethylene-Reflected Plutonium Metal Sphere: Subcritical Neutron and Gamma Measurements, Sandia National Laboratories, SAND2009-5804.
10. Croft, S., A. Favalli, D. Hauck, D. Henzlova, and P. Santi. 2012. Feynman Variance-to-Mean in the Context of Passive Neutron Coincidence Counting, *Nuclear Instruments and Methods*, A686, pp. 136–144.
11. Bell, G. I. 1963. Probability Distribution of Neutron and Precursors in a Multiplying Assembly, *Annals of Physics,* 21, pp. 243–283.
12. O'Brien, S., J. Mattingly, and D. Anistratov. 2015. Sensitivity Analysis and Uncertainty Quantification of Neutron Multiplicity Statistics using Perturbation Theory, *Proceeding of ANS M&C,* Nashville, Tennessee USA.
13. Bell, G., and S. Glasstone. 1970. *Nuclear Reactor Theory,* Van Nostrand Reinhold Inc.

14. Miller, E., et al. 2010. Simulations of Neutron Multiplicity Measurements with MCNP-PoliMi, Sandia National Laboratories, SAND2010-6830.
15. Miller, E., et al. 2014. Computational Evaluation of Neutron Multiplicity Measurements of Polyethylene-Reflected Plutonium Metal, *Nuclear Science and Engineering*, 176, 2, pp. 167–185.
16. Evans, R., J. Mattingly, and D. Cacuci. 2014. Sensitivity Analysis and Data Assimilation in a Subcritical Plutonium Metal Benchmark, *Nuclear Science and Engineering,* 167, 3, pp. 325–338.
17. Kennedy, C., C. Rabiti, and H. Abdel-Khalik. 2012. Generalized Perturbation Theory-Free Sensitivity Analysis for Eigenvalue Problems, *Nuclear Technology,* 179, 2, pp. 169–179.
18. Wang, C. 2013.Exact-to-Precision Generalized Perturbation Theory for Nuclear Reactor Analysis, PhD thesis, North Carolina State University.

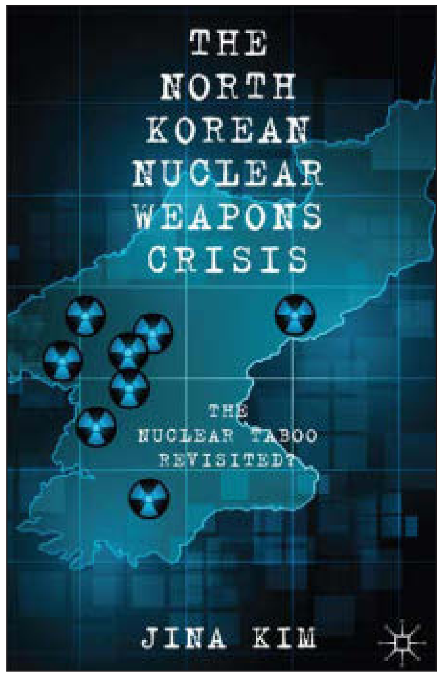
Book Review

By Mark L. Maiello, PhD
Book Review Editor

The North Korean Nuclear Weapons Crisis

Jina Kim

Hardcover, 218 pages
ISBN 978-1-137-38653-3
Palgrave Macmillan/St. Martin's Press LLC, New York, 2014



Not all scholarly works benefit from a treasure trove of facts and details. Sometimes there is too much data. The effort of the writer must be to tease out the most salient issues, arrange them in a manner consistent with the goals of the book, and present them in a cogent discussion that is accessible to the intended audience. It is not an easy task and it is not always successful, as any professor (who essentially does similar work preparing lectures), historian, or writer of non-fiction will tell you.

Jina Kim's work clearly is blessed by an abundance of information concerning the threat to the nonproliferation regime that North Korea poses. The information is offered in six chapters under a political science umbrella designed to explore the book's subtitle: The Nuclear Taboo Revisited? The taboo she refers to is the denial to develop nuclear weapons, and not as she is careful to point out, the denial of their use. Kim seeks to examine how the North Korea's negative identification as an outlier state and its negative interactions with the United States and its Southeast Asia partners contributed to the crisis. She patently rejects the North's behavior as irrational. In her analysis, there are credible motivations for the regime's behavior.

The treatise is divided into a section on the "first" DPKR nuclear crisis, followed by chapters on North Korea's negative identification (its view of itself and its relation to other members of the international community), another on its negative interaction with the five negotiating nations with emphasis on the United States, a chapter on the "second" crisis, and a final section reviewing the negative identification and interactions the DPKR experienced from it.

There is much detail here, packed into a dense narrative that, despite its overabundance of detail, must be cited for the factual gems it contains that are crucial to understanding the DPKR. Take for example, the section on North Korea's guiding social principal of *Juche* ideology found in Chapter 3. This philosophy stresses national autonomy, self-reliance, and self-respect. It has been infused into the daily lives of North Koreans since 1972 when it was embedded in a new constitution adopted by the Supreme People's Assembly. Its importance arises when North Korea confronts international rules that require obedience to an external agency. The International Atomic Energy Agency (IAEA) is one such body that presents a philosophical dilemma for the DPKR. For the North, cooperation while tolerating the presence of foreign inspectors with clear discovery and reporting intentions when fervent independence and self-sufficiency has been the long-standing commandment of the day is, at best, very difficult. Another example is the *Songun* policy, implemented during the period of the second nuclear crisis. This simply put, means that the DPRK places the military above all else even at the expense of the well-being of its citizenry. Alarming in its outcome, the *Songun* policy stresses the importance of the military for the protection of socialism. Since the fall of socialism in Eastern Europe, the DPRK has stressed its solitary struggle to defend socialist ideals.

Though the explanations of *Juche* and *Songun* are clear and become clearer and more relevant as one dives further into the book, other external factors perhaps mitigate against clarification and a full understanding of the behavior of the DPKR. One of these may be an American, and perhaps an international prejudice, against North Korea. This nuclear crisis has been so long in the making and the actions of the DPKR so frustrating, rash, and seemingly irrational at times, that statements of fact that seek to explain the apparent irrationality can run up against a wall of chauvinism, intolerance, and incredulity constructed by the outsiders the North must deal with. It can be presumed that the actions of the DPKR have been so despicable that no depth of factual explanation for them can have any credence or assist in the search for a solution to the crisis. This is, to put it mildly and kindly, most unfortunate. But this is exactly what Kim is attempting to do here.

This is a concerted effort to seek reason behind the apparent aberrant behavior of North Korea. Such an analysis is welcomed. However, to execute this for a general readership (my take is that Kim clearly means her audience to be political scientists), due the aforementioned presumptions of intolerance and I daresay hostility directed to the DPKR, requires great skill. But even in a scholarly venture such as this, the author's interpretation of the North's behavior—the "excuses" to use a crude word—can leave a reader feeling as if thy are a bit "too convenient" for the agenda the North Koreans are pursuing. Often it seems, their pronouncements and philosophies, legitimate in the view of Ms. Kim, seem to provide the North with a flimsy justification for its less-than-sterling behavior. It is one thing to pronounce a philosophy of autonomy and independence from foreign interference, but it's another to sign the Nuclear Nonproliferation Treaty then break from it and claim unfair foreign (IAEA) interference. We know that everything the DPRK does is meant to buoy the regime and we know that the author wishes only to transmit these as details and objective facts that international negotiators must understand, but the reader may not always perceive this. This then is where prejudice can creep in with the potential for a misread of the book. The abhorrent behavior of the North Korean regime can be explained, the author's contends, on the basis of certain internal constructs. To understand it requires that the reader discard any prejudgments about the nation and its behavior to date.

A narrative as detail-rich as this one would ordinarily be considered an advantage; however, the various sections of the book read somewhat like a series of *The New York Times* articles. They are replete with facts that make logical sense but one must remain diligent to maintain the cohesiveness and threads of the author's argument. As a result, one can feel as if there is too much information in the discourse. The inexperienced reader can become lost once immersed in the specifics. As a result, the narrative sometimes reads like a review of every dispute that the DPKR had with its adversaries in the nuclear crisis. It's not a terrible result—the facts are illuminating—but one does not feel satisfied that the author achieved her goal of explaining why the North and the rest of the world are at the current unresolved situation. The reasoning and the conclusions are there. It's just not an easy road to them.

Perhaps, then, the strongest portion of the book is its ending, summary chapter. Here, we can rely on the author to point out what her analysis did achieve. In brief, it indicates that the unresolved issues of the crisis are almost sure to reemerge in future negotiations. It is also clear that an understanding of the domestic beliefs of the DPKR can assist to predict its behavior. The uncoordinated efforts of the China-hosted negotiations need to be revamped to avoid the miscues that allow the North to take advantages in previous negotiations or to take actions antithetical to their spirit. Slow implementation of what was agreed upon bred suspicion of United States' intentions in the North while fostering a belief that the United States was disrespectful of North Korea. Such practices also need repair to foster future negotiations that will achieve significant results for both sides. Most significantly, the author concludes that evidence exists indicating that future negotiations are warranted. The willingness of the DPRK to suspend components of its nuclear program if its demands are met leads to the possibility that a way out of the crisis exists. Respect paid towards Pyongyang and a prioritization of its demands—failures of procedure made primarily by the United States in the past—may lead to success in coming years. Mere "stabilization" of the situation, i.e., peace on the Korean peninsula as it now stands, is not success. The author highlights unanswered questions that remain to be researched: Will the DPRK-China relationship affect how the North views itself in relation to the world? Will the status of the North's nuclear program affect the security posture of the United States?

Well-researched with nearly fifty pages of notes and a nine page bibliography, Kim's book is, despite the above criticisms regarding detail, very concise coming in at only 149 pages of narrative. This book is undoubtedly useful as a recapitulation of the history that brought us to the current situation but the read is a bit of a heavy lift. Though it is an important edition to the discussion of the DPKR nuclear crisis, it is not for those new to the situation. At times, it feels as though one is reading a rather technical doctoral thesis. This effort may also not appeal to those with limited political science background. Despite these criticisms and the requirement to keep and enter the author's discourse with an open mind, the book must be applauded for its unique mission to unravel the mystery behind the reckless behavior of the North by seeking to explain how that nation views itself and its relationship to the rest of the world.

Taking the Long View in a Time of Great Uncertainty

Sometimes Life Seems Too Complicated

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

As I write this column, the terrible terrorist attack in Paris is still fresh in everyone's mind, Belgium's prime minister has established the highest terror alert for a sustained "serious and imminent" threat, and Russia has determined the downing of its Metrojet airliner over the Sinai was a result of a terrorist bomb. Intelligence assets have joined forces to find the planners of the Paris attack, and representatives from many nations are gathering to develop strategies for addressing the international concerns of a growing threat to freedom and democracy. All of these events come at a time when there are many critical uncertainties that could impact the Institute, as addressed in last issue's column, "*A World Full of Critical Uncertainties*."[1] In this context, there is a question that many are asking more and more these days: "What happens if one of these terrorist groups obtains nuclear materials?"[2]

Sometimes life seems to be too complicated.

Using Scenarios to Rehearse Future Worlds

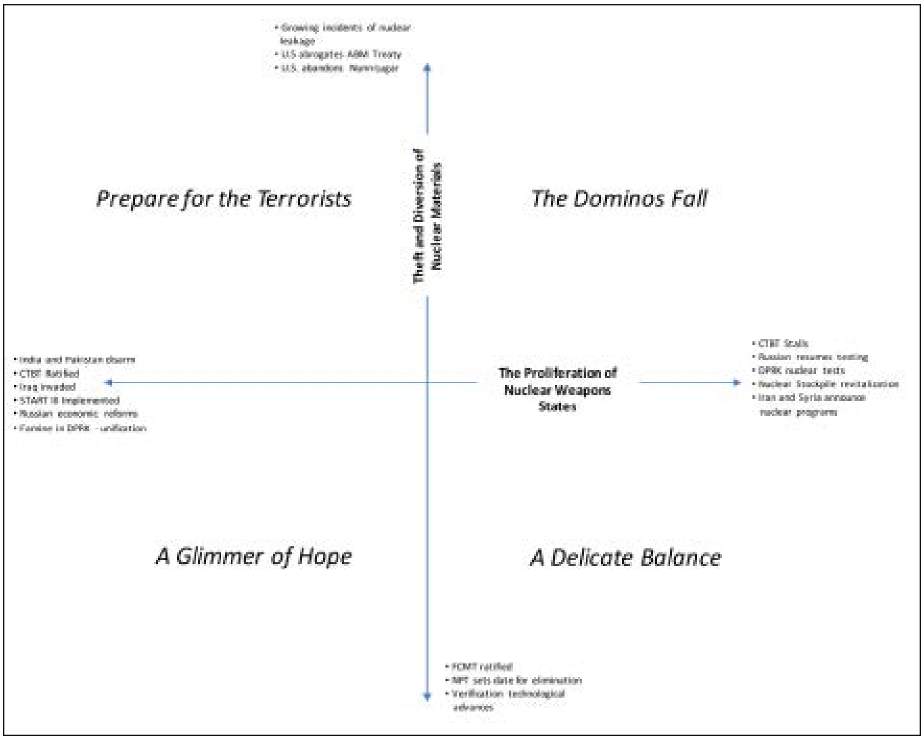
There is no way to make the world we live in less complicated; however, there are planning tools, such as scenarios, that can be used effectively to rehearse possible futures, discuss actions that can be taken as events unfold leading to those futures, and create a greater sense of understanding and ability to address even improbable uncertainties. Scenario planning has been used effectively by large corporations and even governments to address complex technological, political, and social situations. Examples abound in the literature,[3] and the tool is in continuous use these days by organizations to address highly complex issues such as climate change and energy resources.[4] The stories that are created in the development of these scenarios allow managers and policy makers to discuss the worlds in which decisions have to be made, and develop the preparatory actions that need to be taken to accommodate uncertainties.[5]

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.*

Constructing the Scenarios

In last issue's column I indicated that, in its most useful form, scenarios can be shown as an orthogonal construct using descriptors of the two most distinctly different and impactful *Critical Uncertainties*, creating a landscape for four distinct and challenging future worlds.[6] In 1998 I constructed a set of scenarios for a U.S. Department of Energy (DOE) site looking at an otherwise potentially optimistic turn of the millennium, in the context of the underlying critical uncertainties of the proliferation of nuclear weapons technologies and the theft or diversion of nuclear materials. One of the future worlds in that set was named "*The Dominos Fall*." This characterization, posited by Dr. Sig Hecker, former director of the Los Alamos National Laboratory, looked at a troubling time when more and more nations joined the "nuclear club." Figure 1 shows a simplified version of that construct and some of the speculative "end points" that created the future world stories used to stretch the imagination of management. Of particular note, one of the worlds, "*Prepare for the Terrorists*," speculated on the evolution of non-nation-states using nuclear materials in a world that otherwise seemed to be headed toward a more peaceful future, but where those nuclear materials were not adequately controlled, and inaction by leaders created an environment for those actors to achieve their goals.

Figure 1. Global nuclear danger scenarios circa 1998



The introduction to this set of 1998 scenarios came with a prescient warning:

> *As the world enters the third millennium, it teeters on the brink of disaster. With the proliferation of weapons of mass destruction, mankind no longer has the luxury to allow others to exercise unilateral actions in support of extreme agendas. The potential for a single incident to take the lives of millions of people, impact the economy of countries or regions in the trillion of $$, and effect social change of unprecedented scale requires the creation of a new global social conscience and rule of law. Unfortunately, mankind has acquired the power for such destruction before it has developed a responsible social structure. In this unstable world a sequence of discontinuities, particularly those for which an inappropriate, or no response occurs, could lead mankind to those desolate worlds so often depicted by Hollywood. It is of paramount importance that world leadership understands the consequences of their actions or inaction and engages in strategic conversations that identify critical indicators that could lead to the unimaginable…*

Creating Scenarios of Interest to the Institute

Based upon current critical uncertainties, as identified in my last column, one could envision creating a set of future worlds in which strategic discussions pertinent to the future of the INMM could occur. Those future worlds would be created by the nexus of two critical uncertainties on an orthogonal set of axes. One possible set of critical uncertainties that could be used to create those future world stories would be characterized by:

The advancement of nuclear technologies

Global nuclear security threats

The advancement of nuclear technologies might include new national technical means of detecting clandestine nuclear materials and weapons-related activities, research that many of our Institute members are engaged in; or the development of more secure and safe nuclear reactor concepts, such as the advancements promised by small modular reactors.[7] On the opposite side of the axis, it could include darker aspects of the future that would allow individuals or groups to more easily build weapons of mass destruction,[8] or open new paths for the acquisition of nuclear materials or the surreptitious manufacture of those materials.[9]

Global nuclear security threats abound, but have been mitigated greatly by the commitments made by nation-states as a result of the Nuclear Security Summits of the past six years, leading to the enhanced protection of nuclear materials and facilities.[10] However, the once optimistic future that the end of the Cold War offered has suffered setbacks recently as every nuclear weapons state pursues modernization efforts for their stockpiles and delivery systems,[11] and as once-tempered political rhetoric has been over taken by frightening words of nuclear confrontations.[12] The proliferation of nuclear weapons knowledge has forever let the "genie out of the bottle," and despite some perspectives that over time that knowledge can be allowed to deteriorate, the hope for a "global zero" seems farther away than ever.[13]

In future columns I hope to explore the development of a set of scenarios—

"future world stories"—that will capture the imagination of the membership and allow us to better understand the role the Institute can play in this very complicated world. As always, I would welcome thoughts and ideas that can help shape those future world stories.

Endnotes

1. See Taking the Long View Article, "A World Full of Critical Uncertainties" *Journal of Nuclear Materials Management,* Volume 44, No. 1, for a discussion on the Critical Uncertainties facing the world and the INMM today.
2. See http://www.theatlantic.com/international/archive/2015/10/moldova-nuclear-weapons-isis/409456/, and http://www.nbcnews.com/storyline/isis-terror/smugglers-tried-sell-nuclear-material-isis-ap-investigation-n439851; also see "*The Greatest Terrorist Threat: How to stop nuclear material from falling into the wrong hands,*" http://www.nti.org/analysis/opinions/greatest-terrorist-threat/
3. See http://www.generonconsulting.com/publications/papers/pdfs/Mont%20Fleur.pdf for the final report of the "Mount Fleur Scenarios" that helped to prepare South Africa for the end of Apartheid. Also see http://futuristablog.com/the-mont-fleur-scenarios/ and https://www.youtube.com/watch?v=f92RYCZMwEk
4. See http://www.shell.com/global/future-energy/scenarios.html for a rich discussion of scenario planning and its history at Shell Global.
5. There have been many descriptive statements made about scenarios, including "*A modern day hearth for people to gather around and talk about what might be,*" *"A way for people to say 'I am prepared for whatever happens'*," and "*A way to change a person's view of reality.*"
6. The seminal work of creating useful scenarios was presented in Peter Schwartz's book "The Art of the Long View: Planning for the Future in an Uncertain World," which can still be obtained on Amazon.
7. See http://www.energy.gov/ne/nuclear-reactor-technologies/small-modular-nuclear-reactors for more information on the U.S. Department of Energy's programs to stimulate the development of these new energy sources.
8. See "*3-D Printing the Bomb? The Nuclear Nonproliferation Challenge*," http://carnegieendowment.org/2015/11/04/3-d-printing-bomb-nuclear-nonproliferation-challenge/ilcn
9. See NNSA Report "*Prevent, Counter and Respond—A Strategic Plan to Reduce Global Nuclear Threats,*" https://nnsa.energy.gov/sites/default/files/NPCR%20Report_FINAL_(with%20signatures)_3-18-15.pdf
10. See https://www.whitehouse.gov/blog/2015/08/05/announcement-nuclear-security-summit-2016 for information on the fourth Nuclear Security Summit that will be held in Washington, D.C., March 31-April 1, 2016.
11. See "Disarm and Modernize," http://foreignpolicy.com/2015/03/24/disarm-and-modernize-nuclear-weapons-warheads/
12. See "*A New Arms Race Threatens to Bring the U.S. and Russia Back to the Nuclear Brink,*" http://www.huffingtonpost.com/joe-cirincione/arms-race-us-russia-nuclear_b_8557526.html, and "*North Korea Threatens U.S. Nuclear Attack*," http://www.washingtontimes.com/news/2015/sep/15/l-todd-wood-north-korea-threatens-us-nuclear-attac/

13 See "Today's Nuclear Dilemma" by Eric Schlosser, http://thebulletin.org/2015/november/todays-nuclear-dilemma8839

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

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

Name: ________ Phone: ________ E-mail: ________

Memorial Education & Outreach Fund

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

TOTAL $ ________

* 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 88618 • Chicago, Illinois 60680-1618 U.S.A.
+1-847-696-2236 ext. 282 • Fax: +1-847-686-2251 • E-mail: tlaws@inmm.org • Website: www.inmm.org • INMM Federal Tax ID: 31-0740753

April 17–19, 2016
A Technical Meeting on Nuclear Energy and Cyber Security
A Joint Meeting of the Institute of Nuclear Materials Management, the U.S. Naval Academy, and the American Nuclear Society
Annapolis, MD USA

April 17–22, 2016
Tritium 2016
11th International Conference on Tritium Science & Technology
Sponsored in part by INMM
Charleston Marriott
Charleston, SC USA

April 26–27, 2016
INMM Safeguards Culture
Texas A&M University
College Station, Texas USA

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

September 18–23, 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
One Parkview Plaza, Suite 800
Oakbrook Terrace, IL 60181 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.

INMM
INSTITUTE OF NUCLEAR MATERIALS MANAGEMENT

Institute of Nuclear Materials Management

57th Annual Meeting

Save the Date!

July 24 – 28, 2016

Atlanta Marriott Marquis
Atlanta, Georgia USA

www.inmm.org