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Mission Statement

The Institute of Nuclear Materials Management is dedicated to the safe, secure and effective stewardship of nuclear materials and related technologies through the advancement of scientific knowledge, technical skills, policy dialogue, professional capabilities, and best practices.

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President’s Message

By Cary Crawford
INMM President

Friends and Colleagues,

In the last issue of Journal of Nuclear Materials Management (JNMM), I wrote about my experience at the IAEA Safeguards Symposium. The INMM was a cosponsor, which gave me the opportunity to address the symposium at the opening plenary. Since that time, I’ve been back to Vienna for the IAEA Radiological Security Conference. Although the INMM did not enjoy the same presence at this conference, I did have the opportunity to join other international organizations to discuss the planning process for future International Conferences on Nuclear Security (ICONS) and the role these organizations play. The discussions opened doors to conversations about how the INMM can and should relate to such events in the future, and I am encouraged that we will have a much more visible role. We do, however, have work to do to impress on the international community the role that INMM plays in advancing technologies, tools, policies, and research and development in the radiological and nuclear security community internationally.

At the same time I was at the conference, I had the pleasure of attending a 10-year anniversary celebration for the World Institute of Nuclear Security. As you may recall, we recognized this milestone at the annual meeting in Baltimore this past summer. The event in Vienna involved former Senator Sam Nunn; William Tobey, former head of NNSA’s Office of Defense Nuclear Nonproliferation and chairman of the board of WINS; INMM immediate Past President and WINS Board Member Corey Hinderstein; and many other prominent figures in the international nuclear security field, including, of course, WINS Executive Director Roger Howsley. The event included several WINS Academy graduates as well, highlighting the value that a certification in nuclear security provides to enhancing careers in the profession. Having the pleasure of offering the first toast of the evening, I highlighted the fact that INMM started WINS after being challenged by Charles Curtis at the opening plenary session of the 2008 annual meeting. I also highlighted that the INMM takes pride in being an organization that takes challenges — whether of a scientific or a policy-related nature — seriously and can come together to meet some of the most challenging issues in the nuclear materials management professions. WINS is a prime example of this, and they are to be congratulated for their success!

I would like to extend that sentiment to note that the INMM should continue to seek out and highlight our challenges in all aspects of nuclear materials management, whether it be international safeguards, nuclear and radiological security and physical protection, or nonproliferation. A recent example of this is the formation of a new Cyber/Physical Security Integration ad hoc committee to address the growing technological challenges in this discipline to all of our INMM divisions. Presenting these challenges to such a diverse and accomplished set of scientists, researchers, and policy makers is key to continuing our growth as the leading international professional society for the stewardship of nuclear materials and related technologies to enhance global security. I’m proud to be associated with such an organization and look forward to what our next 10 years bring!

Sincerely,
Cary Crawford
President

From The Editor

By Markku Koskelo
JNMM Technical Editor

The JNMM editorial team is pleased to be able to publish another special issue. This was compiled by the organizing committee for the Workshop on Emerging Technologies, Techniques and Methods for Nuclear Materials Science Processing and its Applications to Nonproliferation and Nuclear Forensics that was held at PNNL in May of 2018. I will not try to summarize the content of the various contributed technical papers. I do want to recognize Harrison Kerschner, Mark Engelmann, and Cornelia Brim who helped organize the workshop, and who have written a brief introduction for this special issue. I also want to extend my special thanks to Ken Jarman of PNNL, whose name does not appear in the issue, but whose help has been invaluable to me, and the JNMM staff in coordinating the reviews to make this special issue a reality.

Putting together a special issue is a large undertaking and I am grateful for the effort by the individuals named above, and others, to make this happen. Special issues are a wonderful reference on a specific topic because they highlight the various aspects of the topic, including some of the latest research on the problems that are yet to be solved. I hope you will enjoy this one.

Besides the technical papers from the workshop, this issue contains a book review on an interesting book entitled "Preventing Black-Market Trade in Nuclear Technology". This touches the very mission of the INMM and seems well worth reading. I would also like to highlight the "Taking the Long View" column by Jack Jekowski. He presents an interesting contrast between the past 60 years of international safeguards and collaborations to making things nuclear safe with what lies ahead in the next 60 years. While Jack's columns are always worth reading, this one seems particularly poignant.

Should you have any comments or questions, feel free to contact me, mkoskelo@aquilagroup.com.

Markku Koskelo
JNMM Technical Editor

Nuclear Forensics Prominently Featured at Institute for Nuclear Materials Management (INMM) Regional Workshop on Nuclear Materials Science, Processing and Signature Discovery

Harrison Kerschner
Pacific Northwest Chapter President, Institute of Nuclear Materials Management, Manager, Nuclear Facilities, PNNL

Mark Engelmann
Technical Program Chair, Signatures Science & Technology Division, PNNL

Cornelia Brim
Technical Editor, Scientific & Technical Communications, PNNL

Important scientific developments will change the paradigm for nuclear materials processing and signature discovery, influencing the fields of nuclear forensics, nonproliferation, signature discovery, and the assessment of nuclear security vulnerabilities. To better understand these developments, the U.S. Department of Energy's Pacific Northwest National Laboratory and the Institute of Nuclear Materials Management (INMM) Technical Division for Nonproliferation and Arms Control hosted about 100 nuclear security experts on May 1–2, 2018, in Richland, Washington, USA, for the International Workshop on Nuclear Materials Science, Processing and Signature Discovery. Attendees heard presentations in five focus areas: nuclear material processing and nonproliferation, signature science, nuclear forensics, nuclear material science and its relevancy to treaties and policies, and developing the next-generation experts. The workshop also featured a special session on Introduction to Plutonium.

The workshop was international in scope and represented the largest technical workshop of its kind, with 57 technical presentations and posters.

Noted speakers included:

- Former Ambassador Laura Holgate (U.S representative to the Vienna office of the United Nations and the International Atomic Energy Agency [IAEA]), currently the vice president, Material Security and Minimization, at the Nuclear Threat Initiative
- Mr. David Smith with the Division of Nuclear Security at the IAEA
- Mr. Michael Curry, coordinator for Nuclear Forensics Cooperation with the U.S. State Department
- Dr. Frank Wong, a senior scientist at Lawrence Livermore National Laboratory and former director of Nuclear Defense Policy at the National Security Council during the Obama administration

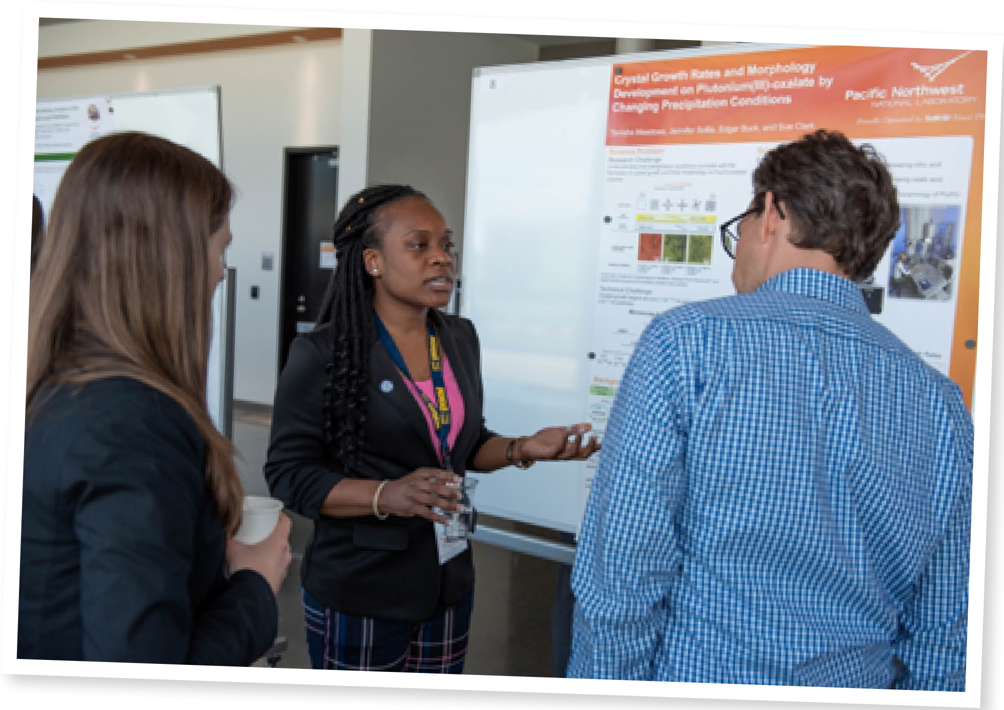
Organizations represented included several Department of Education national laboratories, the U.S. Department of Defense, 12 universities, nongovernmental organizations, research, and industry. Prominent among these were:

- Pacific Northwest National Laboratory
- Lawrence Livermore National Laboratory
- Los Alamos National Laboratory
- Sandia National Laboratory
- Idaho National Laboratory
- Oak Ridge National Laboratory
- Canadian Nuclear Laboratories
- International Atomic Energy Agency
- Joint Research Centre, Institute for Transuranium Elements (JRC-ITU), European Union
- Forschungszentrum Jülich, Germany
- Atomic Weapons Establishment, United Kingdom
- Nuclear Threat Initiative
- U.S. State Department
- U.S. Air Force Institute of Technology
- Federal Bureau of Investigation
- Middlebury Institute of International Studies at Monterey

The papers in this special edition of the Journal of Nuclear Materials Management were selected to represent many of the topical areas from this workshop. Presentations and posters can be found on the INMM website at https://www.inmm.org/INMM-Resources/Proceedings-Presentations/PNNL-Discovery-Workshop.

Chair Mona Dreicer, INMM Nonproliferation and Arms Control Technical Division, and Technical Program Chair Mark Engelmann, Pacific Northwest National Laboratory, kick off the Nuclear Materials Science Processing and Signature Discovery Workshop. (Photo courtesy of the Pacific Northwest National Laboratory)

The poster session of the INMM workshop at the Pacific Northwest National Laboratory featured a variety of topics and garnered much interest among workshop participants. *(Photo courtesy of the Pacific Northwest National Laboratory)*



New Approaches in Process Monitoring for Fuel Cycle Facilities

Benjamin B. Cipiti and Nathan Shoman
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Abstract

Process monitoring (PM) has been part of the safeguards approach for fuel cycle facilities for many years, but its use has been limited. For example, aqueous reprocessing plants may use bulk level measurements to generate a bulk material balance that can be correlated with traditional nuclear material accountancy measurements. However, advanced measurement technologies and modern data analytics approaches may provide new approaches for PM. New facility types may also drive the need for better approaches. Pyroprocessing plants have unique safeguards challenges and unique measurements that could be used to monitor operations. The purpose of the work presented here is to examine improved PM approaches for both aqueous and pyroprocessing facilities. Both unique measurements specific to those facility types as well as machine learning techniques to correlate various data types are being examined. The success metrics are either to improve detection probability or timeliness of detection or to reduce safeguards burden through increased use of unattended monitoring systems. This work relies on safeguards performance modeling to generate simulation data for training followed by diversion or misuse scenarios for testing the approaches. The approaches being considered and preliminary results are presented.

Introduction

The key benefit of process monitoring (PM) data in a bulk handling facility is that often it can be acquired through unattended monitoring. PM data may include electromanometers for tank level, scales for bulk mass, online measurements such as spectroscopy, or nondestructive analysis (NDA) measurements such as neutron and gamma measurements. Current large-scale bulk handling facilities rely on sampling and destructive analysis (DA) for precision actinide measurements to complete an actinide balance. This requires an on-site laboratory and more burden to international safeguards. A long-term goal of international safeguards is to provide the same level of detection probability through use of unattended monitoring only or a reduced need for sampling. PM data may help to achieve that goal or at least reduce inspector presence in facilities under international safeguards.

One difficulty with PM data is that these types of measurements usually cannot quantify actinides to low uncertainty. NDA measurements may have a total measurement uncertainty (random plus systematic) of ± 5–10% for quantifying plutonium. If PM measurements are used to calculate a traditional actinide balance, the overall uncertainty will be too high to meet International Atomic Energy Agency (IAEA) safeguards goals, and diversion detection will be significantly reduced.

The purpose of this paper is to use exploratory data analysis to explore a new approach for international safeguards that can allow use of unattended PM data to meet IAEA safeguards goals without dependence on an on-site laboratory. This approach requires a different way to meet the goals and could be considered in examples where traditional safeguards either will not work or would be too costly.

Background

The IAEA has two main goals in safeguarding a fuel cycle facility:[1]

- Timely detection of diversion of declared nuclear material
- Timely detection of undeclared production or processing of nuclear material

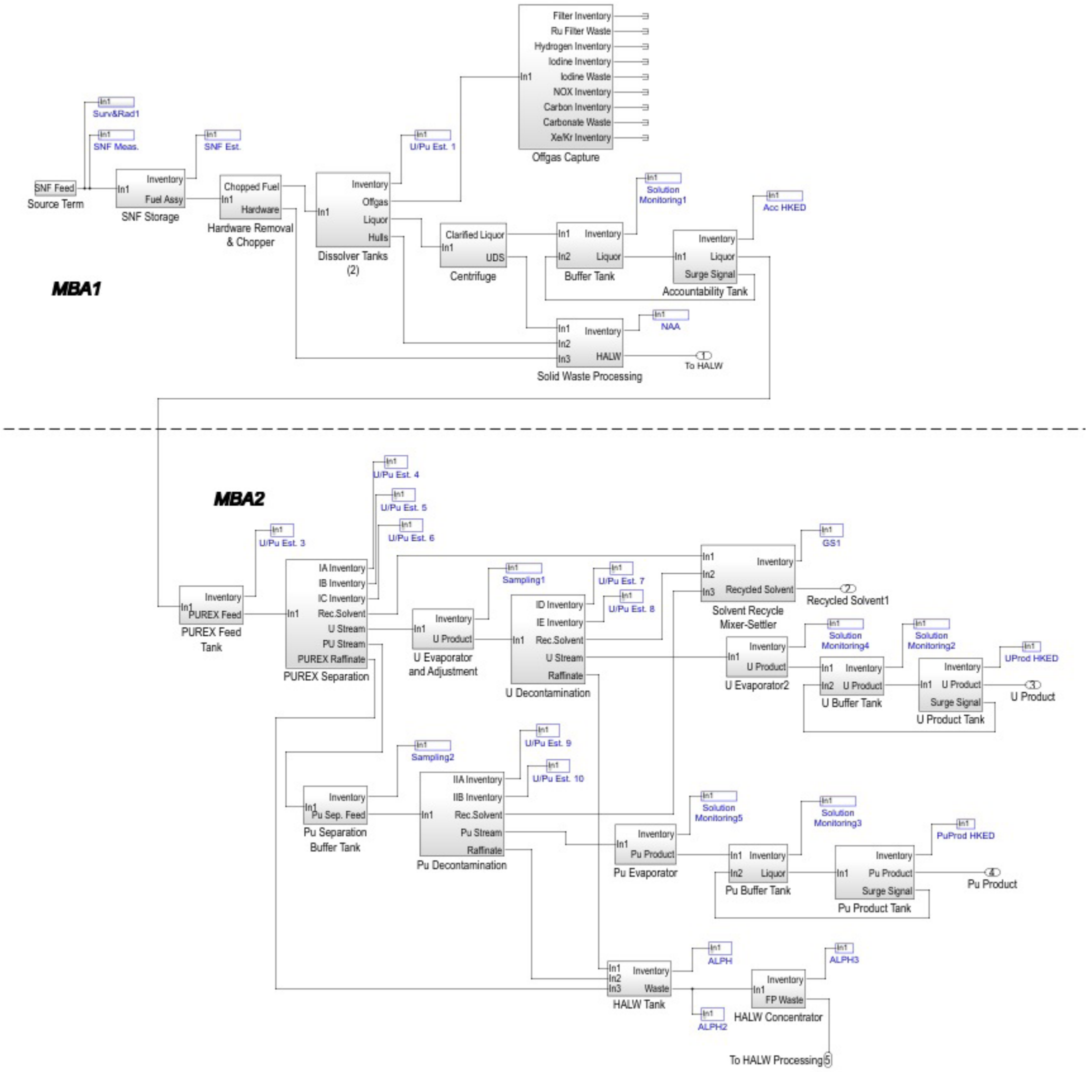

Figure 1. PUREX Separation and Safeguards Performance Model (SSPM)

There are multiple ways to achieve these goals. Traditionally, precision measurements are used on inputs, outputs, and inventory change within a material balance area to perform a material unaccounted for (MUF) calculation. Various statistical tests are applied, each with an alarm threshold, for indicating a diversion. In general, the material balance helps to achieve the above two goals, but the safeguards approach is often augmented with PM, containment, and surveillance.

For reprocessing facilities under IAEA safeguards, the high material throughput and measurement uncertainty needs require significant sampling and laboratory analysis. This has led to the need for an on-site laboratory in the case of Rokkasho.[2] Due to the cost of on-site inspectors and laboratory analysis, there is considerable interest in moving away from the need for an on-site laboratory. Sample shipping is also becoming problematic, so reliance on other laboratories is also less desirable. In an ideal case, the IAEA would like to be able to safeguard a facility with unattended monitoring only (or reduce inspector presence), which generally requires NDA that can be done automatically. The purpose of this paper is to explore how new PM approaches could enable such an approach while still achieving the same IAEA goals.

This work relies on modeling and simulation to examine advanced PM approaches. The Separation and Safeguards Performance Model (SSPM) has been used to provide training data and test the concepts under various scenarios.[3,4] Multiple versions of the SSPM exist, including PUREX, UREX+, and electrochemical models. These models use Matlab Simulink to track elemental and isotopic material flows through various unit operations. Measurement blocks are used to simulate materials accountancy and PM data, and these data are fed into an inventory difference or a machine learning calculation. Diversion scenarios are used to determine the effectiveness of a safeguards design.

Figure 1 shows a PUREX SSPM version. The gray blocks represent the processing vessels throughout the plant and contain significant detail about inventories, timing of operations, filling/emptying sequences, etc. The signals connecting the blocks contain the mass flow information of all nuclear material and bulk flows. The models need to be self-consistent, which is important for PM because small changes sometimes propagate through a facility. The blue blocks represent measurement points and feed into an overall material balance calculation.

Figure 2 shows an SSPM electrochemical version, along with callouts for the various measurement points. The operation of the model in Simulink is very similar, but with differences appropriate to molten salt processing of nuclear material. All models contain the ability to turn on material diversions from various locations to examine the effect on overall plant safeguards. Capabilities include:

- Spent fuel source term library for user-defined runs
- Mass tracking of elements 1–99, full isotopic tracking, bulk solids/liquids tracking
- Integration with GADRAS (Gamma Detector Response and Analysis Software)[5] to simulate gamma spectra
- Customizable measurement points with user-defined errors
- Automated calculation of MUF and errors in real time
- Statistical tests to set alarm thresholds
- Diversion scenario analyses
- Integration with PM data and physical protection systems

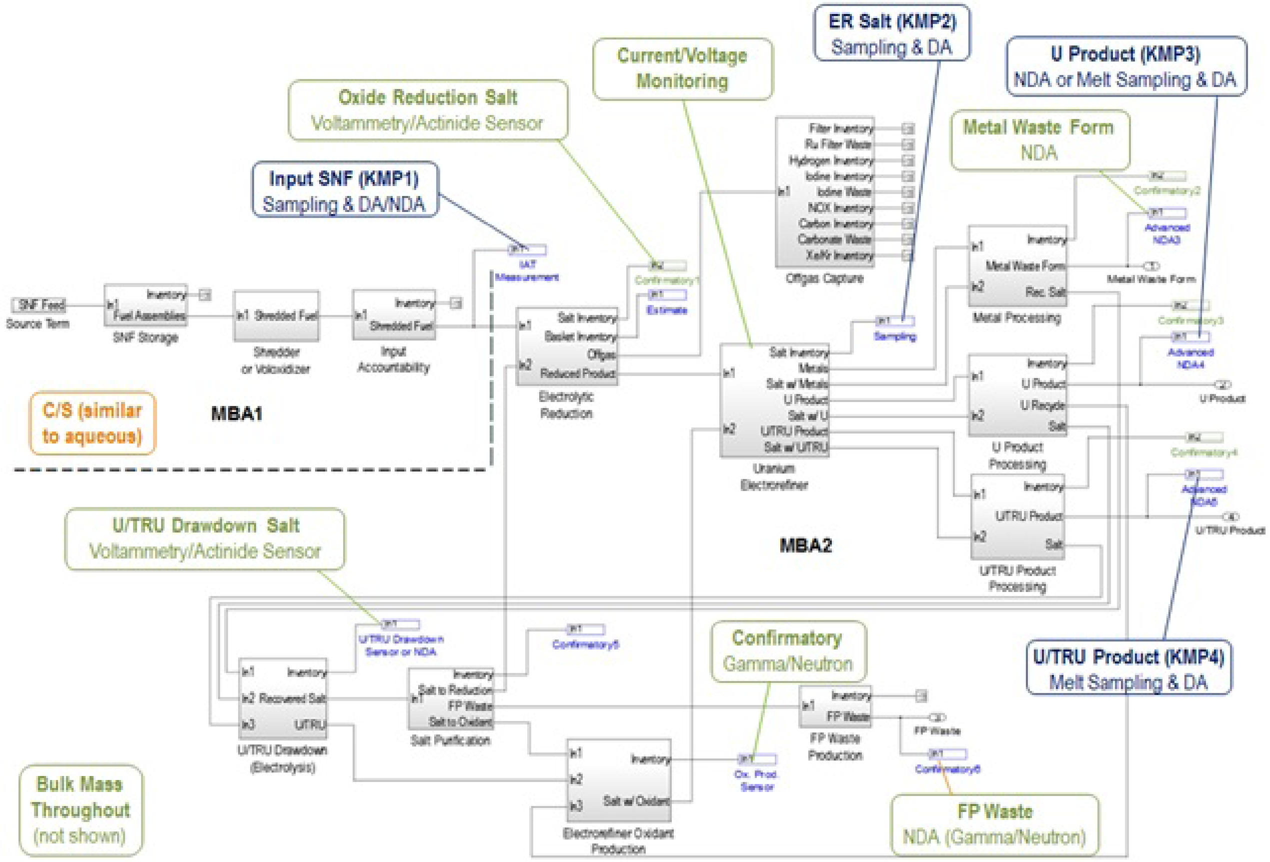

Figure 2. Electrochemical SSPM

The models provide a virtual platform for various applications. Safeguards analyses require a systems-level approach, and only the uncertainty of the measurements is required to determine overall performance. The simulated measurements can be expanded if different types of PM measurements are required. The models have been used for determining the improvement of new instrumentation; examining the integration of new approaches, such as more reliance on PM; performing diversion scenario analyses; providing virtual plant data; and providing a platform for training and education.

New Safeguards Approach

A new safeguards approach is proposed for consideration. This approach requires a different way of looking at the problem, but it could potentially meet IAEA safeguards goals with very little or no DA, and instead more reliance on unattended monitoring.

Bulk Mass Balance

Bulk mass or level data has a lot of value in a material balance since measurement uncertainties may be much lower than sampling and analytical measurements. Precision scales and electromanometers can determine mass with 0.1% random and systematic measurement uncertainty, so direct material loss (whether abrupt or protracted) can often be detected rapidly. The drawback is that a bulk mass balance cannot detect a substitution diversion, in which material is removed and replaced with a surrogate.

A bulk mass balance is relatively straightforward to set up, and standard statistical tests can be used to detect material loss. This type of system already exists in the Solution Measurement and Monitoring System at Rokkasho.[6] This system comprises both joint use and operator-owned electromanometers to track bulk material in the main separations area of the plant. Changes in one tank upstream can be correlated with changes seen downstream. The measurements are unattended, so they are ideal for IAEA use.

Bulk mass measurements should also be relatively straightforward for pyroprocessing. Scales can be used for transfers of material and on certain pieces of equipment. A triple bubbler is being examined for salt level and density measurements for the larger salt vessels.[7] These measurements can be made with low uncertainty to detect direct loss.

Addressing Substitution Diversion

While the bulk balance can detect direct loss, additional measures must be in place to also detect a substitution loss. A substitution diversion involves removing material and replacing it with an equal amount of a surrogate to “beat” the bulk balance. The surrogate, though, is unlikely to match the gamma and neutron emission from the original material. Therefore, a safeguards approach may provide an indication of material substitution that could then be verified (with sampling, for example) to determine if Pu has been diverted. Another approach is for IAEA to continue to draw DA samples and only analyze samples if there is an indication of substitution.

NDA usually can quantify Pu only through indirect measurements (such as fission product peak measurements), especially for samples with mixtures of transuranics and/or fission products. The subsequent correlation to Pu content leads to higher measurement uncertainties for NDA. However, substitution diversions provide indicators that can be measured with lower uncertainty than for Pu quantification. For example, if a dissolver solution is removed and replaced with uranyl nitrate, the fission product content will decrease. This step change may be detectable through gamma measurements. Examination of specific fission product peak heights can indicate if a step change has occurred. The NDA measurements can still be used for the material balance calculation, but the higher measurement uncertainties could be balanced by the new PM approach presented here.

Past work on the Multi-Isotope Process (MIP) Monitor[8] provided a good first step in this direction. This work used gamma detectors to detect changes in reprocessing solutions to try to indicate off-normal events. Principle Component Analysis was used to monitor for possible changes. The work presented here is an extension of the MIP concept in that multiple NDA signals are examined together with multiple bulk measurements to look for inconsistencies. A different machine learning technique is being applied.

NDA Challenges in Support of Change Detection

The use of gamma or neutron measurements has challenges for use in this approach. Gamma measurements provide the potential to measure a number of different peaks to indicate unusual activity. However, the cesium peak typically dominates spent fuel, so applicability will vary by location in a reprocessing facility. After fission products are removed, there is a higher chance of seeing additional peaks, but even small amounts of residual fission products can dominate spectra.

Self-shielding is another challenge. The shielding from canisters or the material itself blocks most of the internal gamma rays, making it difficult to rely on as an indication of material removal. Small, uniform samples may be required to eliminate self-shielding concerns.

Another problem is that real reprocessing facilities process a variety of spent fuel types. There is a natural variability in the isotopic content depending on the fuel feed. Therefore, changes in gamma or neutron emissions do not necessarily indicate a diversion.

Neutron measurements do not have a shielding issue; rather, they are just a total gross count. With long enough counting times, neutron measurements can determine net decreases of actinides with lower uncertainty, but the measurement is mainly detecting curium.

SSPM Modeling Results

The new safeguards approach was examined using the SSPM for a generic pyroprocessing facility. Previous work had already examined the use of bulk balances for detecting direct material loss, so the analysis focused on substitution diversions. Two substitution diversions were examined, along with the effect on gamma spectra of the material from those locations. This work utilized the integration of the GADRAS code[5] with the SSPM for generating gamma spectra based on the isotopic inventories.

The first example is a substitution diversion of the electrorefiner salt. This scenario assumed that some amount of salt was removed and replaced with an equal mass of salt with depleted uranium chloride. The model ran assuming a varying spent fuel source term to simulate the mixture of fuels that run through a reprocessing facility. Therefore, the gamma peaks can vary for two different fuel batches under normal operation. The model was then set up to run a substitution diversion scenario over one batch. Figure 3 shows the results of a simulated gamma spectra for a normal batch and the batch with the substitution. For both batches, a measurement was taken before the U/TRU extraction, after the U/TRU extraction, and after the U/TRU drawdown. For the "Normal Batch" case, the gamma peaks from the three measurements all fall on top of one another. However, for the "Diversion Batch," the peak height changes due to the removal of the fission products when the salt is substituted. This spread is detectable and indicates a substitution diversion.

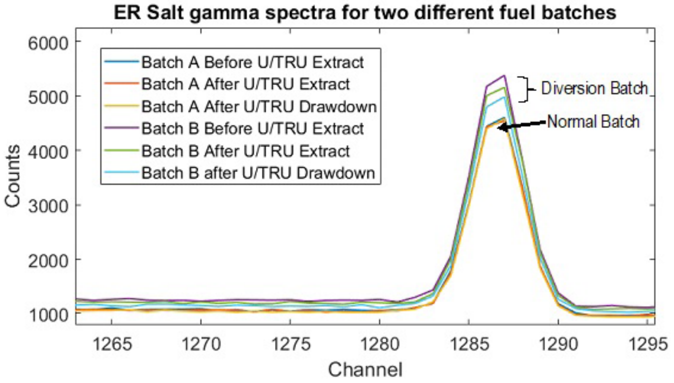

Figure 3. ER salt gamma peak during one normal batch and one substitution diversion

The second example is a substitution diversion of the U/TRU product. This diversion assumed that some of the U/TRU product was removed and replaced with depleted uranium. Detection of the diversion using gamma spectra was a bit more complex. Figure 4 shows an example of four normal batches and one batch with a substitution diversion. The diversion case is indistinguishable from the other normal cases due to the variation in the fuel.

To find an indicator of diversion, the gamma peaks from the U/TRU product needed to be compared to the gamma peaks in the ER salt. Figure 5 shows a ratio of the peaks in the U/TRU product compared to those same peaks in the ER salt right before the extraction. The circles on the plot show the ratios under normal conditions, indicating a large amount of variability. The triangles show the ratios under a substitution diversion — the second peak shows a significant departure from the normal data, indicating a way to detect the diversion.

Both of the examples show that there are signatures of substitution diversions that can be detected even with normal variations in material flows. More work is required to analyze which gamma peaks provide the best indicators. Multiple peaks and additional measurements can be used. The next step is to develop a machine learning algorithm that can analyze all the data.

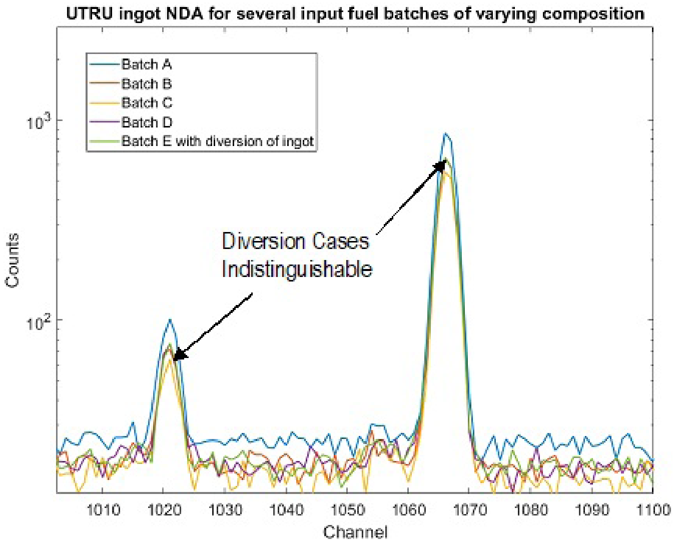

Figure 4. U/TRU product substitution compared to normal products

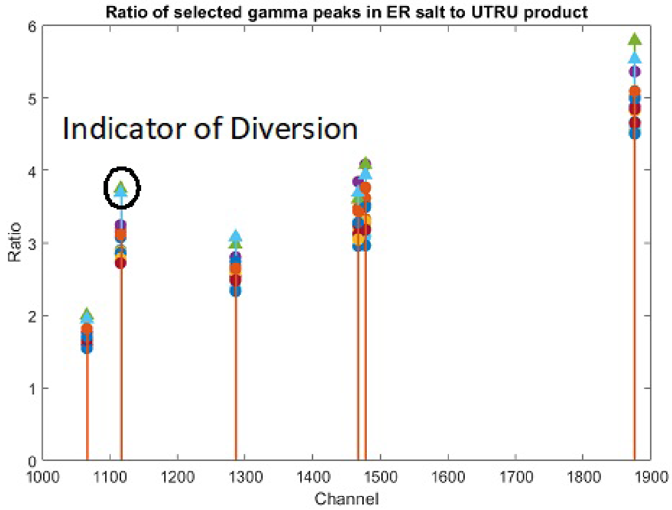

Figure 5. Ratio of gamma peaks comparing a diversion of the U/TRU product to normal runs

OCSVM Methodology

The One Class Support Vector Machine (OCSVM) is an unsupervised machine learning technique that has promise for this application. It can be trained with normal data only, which is desirable since actual fuel cycle facilities will not be able to provide data for diversion scenarios. The OCSVM can take any number and type of input data streams and generate a boundary around normal data such that some defined percentage of points fits inside the boundary. For example, for reprocessing facilities, the OCSVM will use disparate data from a variety of sensors and measurements to identify a data cluster such that approximately 95% of the data falls within some decision boundary. This provides a "fingerprint" of what normal operation looks like. The test is set up to modify this decision boundary to balance false alarm probability with sensitivity to off-normal events. An off-normal event is likely to fall outside the decision boundary. The OCSVM will produce a classification of 1 (normal) or –1 (off-normal) at each point in time that the calculation is applied. An alarm may be reached when a certain number of off-normal classifications occur in a row.

The OCSVM approach will take considerably more effort to develop and train the test for the applications discussed in this paper. Future work will develop the machine learning approach in more detail. A significant amount of data analysis is required for this work since it requires multiple runs producing large sets of isotopic data that are then fed into GADRAS to generate simulated spectra. The analysis of the spectra then must be automated. For future work, the detector response function in GADRAS will also need to be varied to provide more realism for measurements in actual facilities.

Conclusion

The new approach described in this paper is more feasible for a new facility, where the technology can be built into the plant. It would be difficult to apply these changes to an existing operating facility. The approach requires a different way of thinking about the problem by breaking it down into the detection of direct and substitution diversion scenarios. The preliminary results shown here show promise in the ability to detect indications of small substitution diversions using NDA measurements. While pyroprocessing was used for the results presented here, the same approaches could apply to aqueous as well, and future work will explore application to both facility types. This approach may allow for a reduction in inspection efforts at facilities under IAEA safeguards by analyzing DA samples less frequently and potentially increasing the timeliness of detection. A much deeper dive of the concept and training of a machine learning algorithm will be required to move this work forward.

Keywords

Machine learning, process monitoring, OCSVM, international safeguards, safeguards modeling

Acknowledgments

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Author Biographies

Ben Cipiti is a principal member of the technical staff at Sandia National Laboratories, with over 14 years of experience on safeguards and security for nuclear fuel cycle facilities. He received his PhD in nuclear engineering from the University of Wisconsin–Madison and his BS in mechanical engineering from Ohio University.

Nathan Shoman is a member of the technical staff at Sandia National Laboratories, with an MS in nuclear engineering from the University of Tennessee. His current work focuses on developing machine learning approaches to data from facilities such as molten salt reactors and electrochemical reprocessing plants.

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Prospects for U.S.-Russian Strategic Arms Control After the 2018 Nuclear Posture Review

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Abstract

The Trump Administration's release of its 2018 Nuclear Posture Review (NPR), coupled with developments in the U.S.-Russian relationship over the Administration's first two years, make the prospects for the New START Treaty and any extension or successor arrangement less certain than at any point in recent memory. While the NPR still applauds the goal of "the ultimate global elimination of nuclear [...] weapons" in principle, it expresses deep skepticism about the de facto readiness of U.S. counterparts to pursue negotiations in good faith toward further nuclear reductions and disarmament given the current security environment, as competitors have not followed the United States' lead in pursuing that goal.[1] Taking the 2018 NPR into account, this paper recommends that signaling U.S. intent to extend New START as soon as feasible represents a "good deal" for U.S. interests. Specifically, this paper:

- Offers an initial assessment of a suite of options available to the United States for its strategic arms control framework with the Russian Federation, with primary emphasis on options for the New START Treaty;
- Discusses the implications of the 2018 NPR and related developments for the New START Treaty's extension prospects;
- Reviews and assesses policy, legal, and national security implications for several future New START scenarios, including treaty preservation without extension, treaty extension, revision, abrogation, development of a new arms control framework, and treaty violation;
- Offers messaging and talking points using arguments delivered in layman's terms for why signaling U.S. intent to extend New START as soon as feasible is a good deal for the United States.

Introduction

The future of arms control in general and U.S.-Russian strategic arms control in particular is profoundly uncertain. Recent developments that call that future into question include the release of the Trump Administration's February 2018 Nuclear Posture Review (NPR), allegations that Russia carried out a Chemical Weapons Convention- (CWC-) prohibited nerve agent attack on NATO soil and has abetted chemical weapons use by its ally Syria, a bellicose speech on nuclear weapons by President Putin.

While these developments affect prospects for a number of arms control treaty regimes, the focus of this paper is on strategic nuclear arms and, specifically, the treaty between the U.S. and the Russian Federation on Measures for the Further Reduction and Limitation of Strategic Offensive Arms (also known as New START), which is scheduled to expire in 2021 unless both sides take action to extend it for an additional 5 years.[2] If the treaty expires without extension or replacement, the nuclear arms race between the world's two largest nuclear weapon states will be unconstrained by any strategic arms limitation agreement for the first time since the SALT I Treaty entered into force in 1972. Even while the treaty remains in force, the mere prospect of this 2021 expiration scenario is itself of concern from a strategic stability perspective.

Given these worsening prospects, a multidisciplinary team of arms control technical, policy, and legal experts from Pacific Northwest National Laboratory (PNNL) conducted an internal assessment of four of the most likely possible outcomes for the future of New START, ranked in increasing order based on their potential "disruption factor" from the strategic stability perspective. This analysis was enhanced to reflect shifting policy guidance in the 2018 NPR on the relative importance of U.S.-Russian arms control and is published herein for the first time.

NPR Impacts on New START

The NPR[1] is firmly grounded in the new paradigm reflected in the December 2017 National Security Strategy,[3] which emphasizes "peace through strength" and views U.S.-Russian relations through the lens of "a new era of great power rivalries" in which Russia seeks "to shape a world antithetical to U.S. values and interests … investing in new military capabilities, including nuclear systems that remain the most significant existential threat to the United States."[3] This language shifts the focus of U.S. national security efforts from the top Obama-era priority of preventing weapons of mass destruction proliferation to rogue states and terrorists back to a Cold War-era emphasis on Russia (and China) as the primary threat.

As others have noted — among them, former Deputy Administrator of the National Nuclear Security Administration (NNSA) Madelyn Creedon in a recent editorial — the new NPR retains much continuity from the 2010 Obama-era NPR, but its "tone and tenor" are markedly more confrontational.[4] For instance, the 2018 NPR starkly emphasizes deterrence and nuclear arsenal modernization over arms control and diplomacy. While the search for strategic stability drove the negotiation and entry into force of the New START Treaty in 2011, strategic stability in the 2018 NPR is to be primarily advanced not by arms control and nonproliferation cooperation, but by the strengthened deterrent of modernized, "flexible, adaptable and resilient U.S. nuclear capabilities." For its part, Russia has pursued a similar policy, undertaking an expensive modernization of its nuclear forces and signaling very publicly its intention to develop new offensive capabilities to overcome U.S. missile defense technology.[5] It is worth noting that both countries are engaged in ongoing modernization activities to ensure sustainability and trust in an ever-aging stockpile, as well as researching or developing new weapons that will enhance the capabilities of the stockpile. On the U.S. side, this represents a marked change from previous NPRs, which have emphasized no new military capabilities as part of the modernization effort. Not surprisingly given these strategic shifts on both sides, the broader U.S.-Russian strategic stability dialogue has subsequently been suspended.[6]

The 2018 NPR states that the United States will "seek arms control agreements that enhance security, and are verifiable and enforceable."[1] However, the NPR warns that "further progress is difficult to envision … in an environment that is characterized by continuing significant non-compliance with existing arms control obligations and commitments" and notes that "Russia continues to violate a series of arms control treaties and commitments."[1] Among many of the Administration's oft-noted concerns are persistent Russian Intermediate-Range Nuclear Forces (INF) Treaty violations, ongoing Open Skies Treaty violations, suspended implementation of the Conventional Forces in Europe Treaty, and alleged violations of the CWC, such as the March 2018 poisoning of ex-Russian spy Sergei Skripal on UK territory using a banned Novichok-type nerve agent. Taken together, these developments have strengthened an already profound skepticism by the current Administration of Russian treaty compliance intentions that poisons the atmosphere for considering New START extension. Ironically, both sides' continuing compliance with New START is one of the few remaining bright spots in the bilateral relationship.

Consequently, the NPR places little emphasis on the importance of New START, merely noting that the treaty is in effect through February 2021 and stating that the United States "already has met the treaty's central limits … and will continue to implement the New START Treaty."[1] The NPR makes no commitment with regard to extension, but notes ominously that "progress in arms control is not an end in and of itself, and depends on the security environment and the participation of willing partners."[1] As an aside, a word search of the words "extension" and "extended" in the NPR text yields 12 references to the nuclear arsenal Life Extension Program, 15 references to extended deterrence, and only one reference to extending New START.

INF Treaty and Implications for New START

On October 20, 2018, President Trump told reporters that the United States would withdraw from the INF Treaty, which National Security Advisor John Bolton confirmed shortly afterward, adding that a formal notice of withdrawal would follow "in due course."[7] INF was a landmark treaty signed in 1987 that eliminated an entire class of nuclear weapons, namely ground-launched missiles with a range of between 500 and 5,500 kilometers, along with associated launchers. Additionally, the treaty prohibited the production or flight testing of any new ground-launched intermediate-range missiles (or portions thereof) or launchers.[8] The latter prohibition is at the crux of the United States' stated intention to withdraw, as it has for years argued Russia is violating INF by testing and deploying a ground-launched cruise missile that the United States claims has a range capability of between 500 and 5,500 kilometers.[9]

In the current climate between the United States and Russia, especially in light of the Administration's recent statements regarding its likely decision to withdraw from INF, speculation has intensified regarding prospects for New START. The Administration has repeatedly expressed wariness about the utility of New START — a 2017 interview during which President Trump called New START a “one-sided deal”[10] being one of several examples. In October 2018, while in Moscow for consultations on a range of issues including the likely U.S. withdrawal from INF, John Bolton remarked that the U.S. government is considering its position on the agreement but “does not have a position that we’re prepared to negotiate,” and that the U.S. has “plenty of time” since the treaty does not expire until 2021.[11]

The current NPR, while acknowledging the possibility to extend New START, announces no U.S. policy decision on the matter. Current U.S. policymakers likely take into consideration the muted international response when the United States withdrew from the Anti-Ballistic Missile (ABM) Treaty in 2002, an effort also led by Bolton in his prior capacity as Under Secretary of State for Arms Control and International Security. On that occasion, an unhappy Russia responded by declaring it was no longer bound by START II (which had never entered into force), but Russia did not oppose the Strategic Offensive Reductions Treaty (SORT), which entered into force shortly thereafter, rendering START II largely obsolete in any case.[12] However, the stakes are much higher today. If the United States officially withdraws from INF and New START is allowed to expire in 2021, or if either party withdraws earlier, the United States and Russia will find themselves in a position they have not occupied since 1972 — with no constraints or limitations on their nuclear arsenals. Such an outcome would undoubtedly throw into question the two states’ obligation to fulfill their commitments under Article VI of the Nonproliferation Treaty (NPT) to continue negotiations on an end to the arms race and to nuclear disarmament, which could in turn provoke a backlash in the NPT Review Conference process and destabilize the global nuclear nonproliferation regime.

Four Options for the Future of New START

This paper anticipates four of the most likely possible outcomes for the future of New START, ranked in increasing order based on their disruption factor from the strategic stability perspective:

Option 1: Leave New START in Place

This option has the least negative impact with regard to disruption factor. Until recently, given the White House’s continuing focus on other matters not central to strategic stability, such as border security, illegal immigration, and trade imbalances, there was little reason to anticipate an Administration decision on New START in the near term. Continuation of the status quo, as evidenced during the first two years of the new Administration, seemed increasingly likely. It is possible, however, that Bolton’s appointment as National Security Advisor may make an announcement on U.S. policy regarding New START more likely. The Administration’s recent declarations on INF reinforce this prospect. Several suboptions under this outcome are possible. They are listed here in approximate order from most to least probable.

Announce no extension will be sought, and do not initiate negotiations on a new treaty

This policy would eliminate all U.S. and Russian ceilings on strategic nuclear arms after 2021, resulting in substantial loss of transparency and increased tensions since, for the first time since the 1970s, there will be no constraints or limitations on each country’s strategic nuclear forces. This decision would also generate significant negative impacts for both the United States and Russia at the 2020 NPT Review Conference, where the nonaligned states would undoubtedly challenge even more strongly than usual the two nuclear superpowers’ commitment to their Article VI disarmament obligations in the NPT.[13]

Pursue a 5-year extension

Such a move would extend the transparency and stability benefits currently enjoyed by both sides for another 5 years, but this decision does not appear likely in the near term, and possibly not until after the 2020 election. Extending New START was one of the first issues President Putin raised with President Trump in January 2017.[14] At that time, President Trump was unwilling to commit. Without Russian concessions on other arms control topics such as INF and CWC compliance, it seems unlikely that Russia skeptics such as Bolton would advocate for this outcome — though President Trump has occasionally expressed concern over the arms race.[15]

Initiate negotiations on Next START (the New START successor agreement) in either the bilateral or multilateral context

A new multilateral agreement would be a game-changer, requiring a fully staffed U.S. State Department diplomatic apparatus and arms control–friendly Presidential leadership. On the bilateral front, President Trump could seek a grand bargain that includes both strategic and nonstrategic arms as well as missile defense to strike a "better deal" than his predecessor — a deal that would comply with the stringent verifiability and enforceability criteria in the NPR. Such agreements typically take years to negotiate. Given the significant deterioration in U.S.-Russian relations, there is little evidence to suggest this outcome is likely on its own. A lowest-common-denominator option, like SORT, that involves minimal effort to negotiate, minimal new substance, and leaves the United States and Russia broad discretion to pursue mutual deterrence, seems a reasonably probable face-saving option. A combination of the last two suboptions may also be a feasible path forward.

Option 2: Seek to Amend New START Before Expiry to Negotiate a "Better Deal"

The Administration's high-profile efforts to revise treaties already in force — like the North America and United States–Republic of Korea Free Trade Agreements, among others — suggest that this is a tack the Administration may consider. Potential objectives might include the following: (1) amending the set of treaty-limited items to capture hard-to-track items the Russians are deploying, such as rail-mobile intercontinental ballistic missiles (ICBMs); (2) resurrecting START II limits on multiple independently targeted reentry vehicle ICBMs not currently captured; (3) amending generous counting rules for heavy bombers Russia is leveraging to its advantage; (4) strengthening the already extensive verification regime; and/or (5) strengthening penalties for noncompliance. Any such arrangement would require compromises the Administration or Russia would be unlikely to entertain; moreover, given the Administration's lack of appetite for arms control negotiation, an ambitious or detailed revision here again seems unlikely.

Option 3: Withdraw from New START

This outcome previously seemed unlikely unless one side were to directly and credibly allege a serious New START violation by the other. Currently both sides deem the other to be compliant. However, the likelihood of New START withdrawal increased with John Bolton's appointment as National Security Advisor. He was a leading advocate for U.S. withdrawal from the ABM Treaty in 2002 — a development Russia denounced as the start of a new arms race. As recently as 2017, Bolton stated publicly that New START gave Russia "a decided advantage that we didn't have to give away … The next step in the bilateral relationship with Russia is for this Administration to abrogate the New START Treaty so that we have a nuclear deterrent that's equal to our needs."[16] The Administration's repudiation of the Joint Comprehensive Plan of Action with Iran and the Paris climate accord, which enjoyed high degrees of expert and international support among U.S. allies, additionally suggest that a withdrawal is not only possible, but plausible.

Option 4: Suspend New START Implementation or Violate the Treaty Without Withdrawal

This might be done to pressure Russia on INF compliance. The authors cannot rule out this possibility. In the FY18 National Defense Authorization Act, Congress authorized $58 million to begin research into a ground-launched intermediate-range cruise missile. Although such research and development is not in violation of the INF Treaty, flight testing of such a missile would be.[17] It is conceivable that a similar thought process could be applied to New START, such as maintaining a higher-than-allowed number of launchers or delivery vehicles to add additional pressure to Russia to come into compliance or otherwise resolve outstanding concerns regarding treaty violations.

Results

The authors believe each of the three discrete outcomes below is reasonably likely and note that the Administration could choose to pursue multiple outcomes in parallel, which the authors also regard as reasonably likely. These outcomes reflect the first three "more probable" options presented above. The authors regard the fourth option above as comparatively unlikely, and in any case unnecessary, given the demonstrated willingness and ability of this Administration to formally denounce past agreements.

1) **The sides may agree to discuss an extension of New START now that the new NPR is released, but the Trump and Putin administrations would likely go through a protracted period of brinksmanship first.** For instance, the United States could threaten to withdraw from New START unless Russia comes back into compliance with the INF Treaty. This may be the game the United States is currently playing with its stated objective to withdraw from INF.
2) **The Trump Administration may seek to negotiate a successor that represents a promised repudiation of the New START approach, potentially emphasizing a more rigorous verification regime than the extensive**

regime already in place, stronger penalties for noncompliance, or broader scope. The U.S. negotiation strategy could also follow the model John Bolton used to negotiate the 2002 SORT Treaty, in which Russia was presented with an abbreviated "take it or leave it" treaty text by a dominant United States, which sought to "minimize constraints and maximize flexibility," while relying on then-current START I verification provisions.[18]

3) **The Administration might allow early New START expiration, or withdraw from or suspend implementation of the agreement, in a manner that would leave it free to pursue expansion of the stockpile.** Given the relatively weak support for New START and arms control more broadly in the NPR, coupled with the departure of moderate Secretary of State Rex Tillerson, his replacement by Secretary of State Mike Pompeo, and the arrival of National Security Advisor John Bolton, this option cannot be ruled out. In light of the anticipated U.S. withdrawal from the INF Treaty, this option is beginning to gain credibility within the arms control community and the Trump Administration.

Conclusion

Given the uncertainties discussed above, the time is ripe for a vigorous dialogue in the national security policy community about why Option 1b (New START Extension) is a "good deal" for the United States. However, "arms control for the sake of arms control" as a guidepost on the path to global zero is an argument doomed to failure with this Administration. Instead, for maximum effectiveness with current U.S. Government stakeholders, arguments in favor of extending New START should be cast in America-first language and conveyed to senior Administration officials through both traditional and nontraditional channels. A few such arguments are as follows:

- We have an opportunity and an obligation to protect the American public. The danger of Russian nuclear weapons poses an existential threat to U.S. survival. One Russian nuclear bomb can wipe Washington, New York, or any American city off the map, and the Russians (like the United States) have many.
- New START preserves parity, preserves stability, prevents a strategic nuclear arms race with Russia, and minimizes any Russian-perceived incentive to attack — making America significantly more secure.
- New START leaves the United States with an ample arsenal of up to 1,550 deployed strategic nuclear warheads. With this arsenal, we can inflict an overwhelming response against any would-be aggressor.[19]
- The New START verification regime is more extensive than other arrangements Russia has violated. Russia has complied with its commitments under New START.19 While sacrificing little, the United States has gained reasonable assurance of continued Russian compliance.
- The winning combination of nuclear arsenal modernization, reinvestment in America's conventional superiority, and verifiable and enforceable arms control are complementary tools that work together to keep America safe.
- We can pursue modernization and other defense drivers laid out in the NPR without jeopardizing New START. In fact, extending New START for an additional 5 years is the smart thing to do. It offers maximum freedom for U.S. defense strategy at minimum cost.
- Extending New START lets us focus limited U.S. dollars on modernizing the nuclear enterprise and maintaining the nondeployed stockpile as a hedge against future threats — all without violating the treaty.
- New START meets the criteria for arms control agreements laid out in the NPR. It is verifiable and enforceable. It boosts transparency, understanding, and predictability.
- New START constrains the Russians from behaviors that would require a prohibitively costly U.S. response (such as expanding the size of our nuclear arsenal). We reap the economic benefits of this Russian constraint, making more resources available for homeland security, job creation, and other America-first imperatives.
- Extending New START buys "credit" for the United States with many international partners, including our allies who strongly support the treaty, and gives us a powerful shield against international critics at the looming NPT Review Conference.
- President Trump often says he wants good relations with Russia. Extending New START would help him achieve that. The move would be praised by President Putin, who continues to express his own readiness to discuss it.[20]

To conclude, extending the New START Treaty is arguably a good deal for the United States, but it is only one of several possible outcomes that could emerge, given the stated policies and priorities of the Trump Administration. To be persuasive in the current political environment, advocates of strategic stability should replace traditional arms control arguments with America-first messaging, delivered through traditional and nontraditional channels in layman's terms like those above, to justify why extending New START is a win for this Administration and the American people.

Keywords

Arms control, New START, strategic stability, Nuclear Posture Review, Russia

Author Biographies

Laura Schmidt Denlinger is a senior nonproliferation advisor and technical team lead for Nonproliferation Treaties and Agreements with a background in diplomacy at Pacific Northwest National Laboratory (PNNL). She has more than 20 years' experience in arms control, threat reduction, and international relations, and has served in a variety of diplomatic positions for the U.S. Department of State — both in Washington, D.C., and abroad. Among other duties, she was the senior U.S. representative and deputy executive director of the International Science and Technology Center in Moscow, attaché for political affairs at the U.S. Embassy in Moscow, and director of the State Department's BioChem Redirect Program — a flagship effort to engage former Soviet biological and chemical weapons scientists in civilian research. Since joining PNNL, Denlinger has been responsible for relationship management and national security engagement with the State Department and is line manager for Nonproliferation Graduate Fellows from a diverse range of policy and technical backgrounds.

David Donnelly is a trained lawyer with a broad spectrum of experience and expertise on arms control policy, nuclear and radiological materials security, public international law, and regulatory best practices. Since joining PNNL in 2013, Donnelly has performed work for the NNSA's Office of International Nuclear Safeguards and the U.S. Department of State Bureau of Arms Control, Verification and Compliance, including multiple projects to analyze legal and policy implications of emerging cyber risks in arms control and nonproliferation regimes. Prior to joining PNNL, he worked for several years as a Russian interpreter, translator, and area specialist for the Departments of State and Justice on issues ranging from arms control treaty negotiation to cybercrime investigations. Donnelly holds degrees from Georgetown University Law Center (J.D., 2013) and Carleton College (B.A. in Russian, 2004).

Jake Benz specializes in the research and development of technologies and approaches to support and enable current and future monitoring and verification initiatives in arms control and international safeguards at PNNL. His projects involve collaboration and technical engagement with domestic and international partners on bilateral and multilateral verification concepts. Benz's 9 years of experience in this area has centered on developing tools and methodologies to generate and maintain confidence in treaty accountable material or items, equipment, and facilities to support potential future verification objectives. His research focuses on two main areas: (1) how to confirm authenticity and integrity of technologies and associated information that may be negotiated for use in a future treaty, and (2) identifying, evaluating, and addressing how cybersecurity interacts with and affects the critical national security missions within nonproliferation, international safeguards, and arms control. These areas span both cyber and physical domain-spaces to ensure the trustworthiness of potential equipment and their impact within a treaty verification regime.

Jennifer Tanner is a staff scientist at PNNL with more than 35 years' experience in the nuclear field. She has worked in the areas of nuclear fuels, international safeguards, radiation transport modeling, and neutron dosimetry and spectrometry. Tanner has worked extensively in measuring and characterizing the neutron fields at commercial reactors and Department of Energy and Department of Defense facilities and in the calculation of radiation dose rates and neutron dosimeter/instrument responses. Additional areas of expertise include radiation shielding, emergency preparedness, nuclear instrumentation, nondestructive assay, and criticality safety. Currently, Tanner manages and contributes to PNNL's projects associated with nuclear warhead reduction transparency and treaty verification as well as monitoring technology development for NNSA clients. She has participated in the U.S./Russian Federation Mayak Transparency negotiations and Trilateral Initiative consultations and cochaired a joint Department of Energy and Department of Defense working group on tamper-indicating devices for use in international arms control and nonproliferation regimes. Recently, she managed the Warhead and Fissile Material Transparency Program and the End-to-End Warhead Monitoring Campaign, both for offices within NNSA. At present, she is responsible for managing the development and implementation of the Monitoring and Inspection regime under the 2000 Plutonium Management and Disposition Agreement and for evaluating plutonium disposition options.

Mark Schanfein was a senior nonproliferation advisor at PNNL until April 2018, working on a broad range of safeguards, security, and arms control issues. At Idaho National Laboratory (INL), he focused on pyrosafeguards for electrochemical separation and other safeguards-related research. Prior to INL, he had a 20-year career at Los Alamos National Laboratory where, in his last role, he served as Program Manager for Nonproliferation and Security Technology. He served as a technical expert on the ground in the Democratic People's Republic of Korea during the disablement activities resulting from the 6-Party Talks. Mark has 8 years of experience working at the International Atomic Energy Agency (IAEA) in Vienna, Austria, in the Department of Safeguards, where he served four years as a safeguards inspector and as Inspection Group Leader in Operations C, and four years as the Unit Head for Unattended Monitoring Systems in Technical Scientific Services. In this position, he was responsible for the installation of all IAEA unattended systems in nuclear fuel cycle facilities worldwide.

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Safeguards Knowledge Management and Retention at the U.S. Department of Energy National Laboratory Complex

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Abstract

The loss of international nuclear safeguards knowledge due to the attrition and impending retirement of many experts has made knowledge retention a priority for the U.S. national laboratory complex. Knowledge retention refers mainly to the preservation and transfer of both explicit (e.g., written, documented, fact-based information) and tacit (experiential) knowledge. In an effort to address this challenge, in 2017 the U.S. Department of Energy National Nuclear Security Administration sponsored four U.S. national laboratories to develop a safeguards knowledge retention strategy. The effort combined workforce analysis tools with a survey and workshop intended to identify critical safeguards knowledge, skill sets, types of safeguards information to retain, best practices, and lessons learned.

The 1-year study applied a multifaceted approach: (1) critical safeguards information at risk of loss was identified using a methodology developed by Oak Ridge National Laboratory; (2) a survey and workshop were conducted to assess nine U.S. national laboratories' efforts to determine current safeguards knowledge retention practices and challenges and identify best practices; and (3) a workforce planning and agility tool developed by Los Alamos National Laboratory was used to identify and predict critical safeguards knowledge gaps and how best to recruit to fill those gaps.

Based on findings of these tasks and research on other organizational approaches to address similar issues, a strategy was developed on potential knowledge retention methods, customized human resource policies, and best practices that could be implemented across the national laboratories.

Introduction

Loss of U.S. safeguards expertise within the U.S. Department of Energy National Nuclear Security Administration's (DOE/NNSA) national laboratory complex due to attrition and retirement is expected to be significant over the next five to 10 years. According to a staffing study conducted by the Oak Ridge Institute for Science and Education, approximately 81 percent of international safeguards specialists ages 45 and older are estimated to leave the field by 2024.[1,2] A consequence of this substantial loss of expertise will be the decline in safeguards knowledge retention and the overall level of U.S. expertise in the field. Critical skills and core competencies such as nuclear material accounting and control, nondestructive assay, containment and surveillance, and safeguards approaches, design, and evaluation will be lost.

In the absence of a knowledge management program, much of the work is passed on only situationally. Staff may receive critical knowledge only if they know who and what to ask about. The absence of knowledge management results in very valuable information about historic work, processes, procedures, contacts, and applications being lost, dooming new experts in the field to repeat those efforts to gain a knowledge foundation. One of the risks in this scenario is duplication of effort using valuable time and taxpayer resources. Moreover, the U.S. Government risks losing its role as a global leader in the field of nuclear safeguards.

Unless immediate, proactive steps are taken, mid-career and senior U.S. safeguards staff members with highly relevant knowledge, skills, abilities, and experience will walk out the door and take their expertise with them.

In 2017, four U.S. national laboratories collaborated in a Knowledge Management and Retention Working Group to explore the safeguards knowledge retention problem, identify possible approaches, and develop a strategy to address it. The 1-year effort featured four primary tasks:

1. Identify critical safeguards information at risk of loss.
2. Assess efforts to determine current safeguards knowledge retention practices and challenges and identify best practices.
3. Develop tools to identify and predict critical safeguards knowledge gaps and how best to recruit to fill those gaps.
4. Based on findings from the first three tasks and research on other organizational approaches to address similar issues, develop a strategy on potential knowledge retention methods, customized human resource policies, and best practices that could be implemented across the national laboratories.

Definitions

As part of this effort, knowledge management and knowledge retention are defined to ensure consistency between project team members and stakeholders. The International Atomic Energy Agency (IAEA) defines knowledge management as "an integrated, systematic approach to identifying, acquiring, transforming, developing, disseminating, using, sharing, and preserving knowledge, relevant to achieving specified objectives."[3] Knowledge management is a broad category that includes both the management and sharing of knowledge to enable individuals to create new knowledge collectively to achieve organizational goals.

The IAEA refers to knowledge retention in the context of a knowledge retention plan, which "identifies critical knowledge and positions in an organization, and methods to be used for addressing potential knowledge loss through attrition, and the process that will ensure that the plan is continually updated to meet changing business needs."[3] In other words, a knowledge retention plan seeks to identify specific critical knowledge at risk of loss and approaches for retaining it. It could be a subset of knowledge management. During a fiscal year 2017 workshop, participants agreed with the IAEA definition of knowledge management. The group further agreed that knowledge retention was part of a solid knowledge management program. Including knowledge retention as a part of a broader knowledge management strategy was especially important to the group as the national laboratories and overall DOE complex face a large portion of the safeguards workforce retiring.

Within these definitions, NNSA safeguards knowledge exists in both tacit (experience-based) and explicit (written, documented) forms. Both forms are required and complementary. It is entrenched in operating instructions, guides, databases, training materials, technical specifications, and procedures that are written down (explicit knowledge). It also exists as tacit subject matter expert (SME) knowledge that can be difficult to transfer to another person by means of writing or verbalizing it since it is wholly embodied in the individual, rooted in practice and experience, expressed through skillful execution, and transmitted through training by watching and doing.[4] Collectively, all of this knowledge forms a knowledge base that needs to be maintained and kept aligned and consistent, both from a historical basis and over time to ensure a complete understanding of current operations. If the knowledge accumulated to date is lost, it may take years to build it back, if that is even possible.

Complementary Efforts

In addition to current efforts being pursued by some of the national laboratories, the working group explored how various organizations are addressing the knowledge management and retention challenge. Such initiatives may offer useful insight for a U.S. national laboratory-focused approach or strategic roadmap.

International Atomic Energy Agency

The IAEA is investing heavily in knowledge management in the nuclear industry. Since 2002, the IAEA General Conference has included topics related to nuclear knowledge management (NKM).[5] The IAEA also has a nuclear knowledge management section within its Department of Nuclear Energy to assist member states in this issue. This section focuses on:

- Developing methodologies and guidance documents for planning, designing, and implementing NKM programs.
- Facilitating nuclear education, networking, and experience exchange.
- Assisting member states by providing products and services for maintaining and preserving nuclear knowledge.
- Promoting state-of-the-art knowledge management technologies and supporting interested member states in their use.

U.S. Department of Energy

The DOE faces a challenge to capture and transfer the knowledge and experiences of its current professionals. According to the DOE 2016–2020 Strategic Human Capital Management Plan, 36 percent of the DOE's (federal) workforce will be eligible to retire in 2020.[6] To address retention of expertise and best practices, DOE has initiated two separate programs.

DOE Knowledge Capture and Transfer Program

The DOE has established a Knowledge Capture and Transfer Program to focus on both explicit and tacit knowledge as well as corporate knowledge (the unspoken rules of an organization, including its culture).[7] The program aims to document the knowledge critical to the DOE mission.

Phased retirement

Phased retirement is a human resources tool used by federal agencies to retain employees who would have fully retired but who are willing to continue in federal service for a period of time on a part-time schedule while mentoring other staff members. This allows managers to provide unique mentoring opportunities for employees while increasing access to the decades of institutional knowledge and experience that retirees can provide. The DOE has recently implemented a phased retirement plan.[8]

U.S. Nuclear Regulatory Commission

The U.S. Nuclear Regulatory Commission (NRC) formalized their knowledge management program in 2006 with the release of a Knowledge Management Program Policy (SECY-06-0164)[9]. The NRC program's primary focus is on identifying knowledge that is both high-value and high-risk (of loss), then capturing and preserving it for access by others.

National Aeronautics and Space Administration

In 2012, National Aeronautics and Space Administration (NASA) established a Chief Knowledge Officer to serve as a single focal point to develop the policy and requirements necessary to integrate knowledge capture across programs, projects, and centers. Some tools used by NASA include:[10]

- *Knowledge Journal* – An ongoing publication that promotes knowledge sharing and communicates lessons learned and best practices, ensuring NASA remains a learning organization.
- My Best Mistake Video Series – An array of stories told by project managers and knowledge practitioners in the NASA community. Each story tells how the author learned a lasting lesson from a mistake.
- Lessons Learned Database – Provides access to official, reviewed lessons learned from NASA programs and projects. Each lesson describes the original driving event and provides recommendations that feed into NASA's continual improvement via training, best practices, policies, and procedures.
- Critical Knowledge Gateway – A portal connecting the NASA community to a vast array of NASA videos and video lessons. The portal is organized into topic areas such as system engineering, project management, operations, etc.
- Knowledge Toolbox – Tools, resources, and information for individuals and teams to enhance their knowledge-sharing efforts on real-life projects and programs.

Results

As part of the 2017 knowledge retention effort, several U.S. national laboratories worked on tasks supporting the identification of knowledge retention issues around the complex.

- Sandia National Laboratories (SNL) circulated a survey to the laboratory complex to determine the current state of safeguards knowledge retention.
- Oak Ridge National Laboratory (ORNL) and Los Alamos National Laboratory (LANL) both worked on tasks to identify competencies and knowledge relevant to safeguards that are at risk of being lost and to identify strategies to address this loss.
- The Knowledge Management and Retention Working Groups at four U.S. national laboratories conducted a workshop to discuss these efforts and to develop a broader knowledge retention strategy (roadmap) for the complex.

Multilaboratory Knowledge Retention Survey

To better understand the status of safeguards knowledge management and retention within the DOE/NNSA national laboratory complex, SNL distributed a survey to nine U.S. national laboratories (Argonne, Brookhaven, Idaho, Los Alamos, Lawrence Livermore, Oak Ridge, Pacific Northwest, Sandia, and Savannah

River) to solicit information on the status of knowledge retention at each laboratory. For example, the survey inquired about attrition of safeguards personnel, processes and procedures or requirements for knowledge retention activities for outgoing safeguards staff members, types of safeguards information that are critical to preserve, factors of influence, challenges and barriers to knowledge retention, and best practices. The survey was designed to better understand challenges and opportunities in key areas of knowledge retention as identified by the respondents.

The multilaboratory survey responses demonstrated both challenges and opportunities in key areas of knowledge retention, such as infrastructure (i.e., access to safeguards information, documents, and knowledge experts), resources and incentives (i.e., limited time, funding, and resources), training (i.e., training, mentoring, effective knowledge transfer), and processes and procedures (lack of formal processes). Based on survey feedback, the following recommendations were identified:

- Infrastructure – Develop a user-friendly, shared platform repository where relevant project materials, training, curriculum, presentations, etc. can be accessed.
- Resources and incentives – Fund and incentivize knowledge transfer and engage in mentoring.
- Training – Fund and evaluate training effectiveness.
- Processes and procedures – Identify and recommend best practices for transition/succession planning, workforce tools, and knowledge transfer.

ORNL Succession Planning Methodology

ORNL developed an initial methodology to identify critical skills for SMEs to aid in succession planning. The initial methodology addressed the processes and procedures recommendations above.

The methodology features the following steps:

1. Select a nuclear facility or group of experts at a DOE national laboratory.
2. Select candidates.
3. Interview candidates.
4. Analyze interview results.
5. Validate critical skills and criticality level.
6. Assess potentially critical skills by listing and ranking them using the IAEA position risk factor scale[11] of 1–5.

To test the methodology, ORNL conducted interviews of seven technical experts. Each interview led to a critical competency analysis based on the questions asked. A table of critical competencies for each SME was developed. The methodology was updated based on the experience gained in the implementation of the initial methodology.

LANL Workforce Agility Tool

LANL is using a data-driven workforce tool designed to help managers identify institutional capabilities based on self-identified competencies of the workforce to facilitate an agile workforce that can effectively support programs with similar competency needs. The tool derives a set of competencies necessary to perform specific mission work based on a database of workforce competencies. The database lists over 6,500 LANL employees and 1,500 competencies, which cover the gamut of technical and operational skills employees identified. Each employee is identified with as many of these skills as they and their line manager choose. The high-fidelity information in this database is used to build a network of competencies.

A team using this tool was tasked with mapping safeguards competencies as identified at LANL, using those results to identify good matches for mentoring and cross-organization collaboration, and identifying related competencies to assist in strategic planning.

To leverage the functionality of the competency-matching algorithm across the national laboratories, other laboratories would also need to use or establish a competency database similar in structure to the database used by LANL. Establishing such a database could add functionality to the capabilities of the safeguards repository currently under development. Repository users could enter a profile with competencies and/or interests when logging in to add documents, thus effectively creating a safeguards-specific competency database within the complex. This database could be used to identify mentoring or training opportunities, knowledge capture priorities, or new trends in safeguards expertise.

Safeguards Knowledge Management and Retention Workshop

On August 29–30, 2017, the working group facilitated a Safeguards Knowledge Management and Retention Workshop. Representatives from nine national laboratories attended. The purpose of the workshop was to clearly identify challenges related to safeguards knowledge retention at national laboratories and to develop recommendations and practical steps to mitigate those challenges. The workshop included presentations and brainstorming sessions. The presentations covered current laboratory initiatives regarding knowledge management. The brainstorming sessions discussed defining knowledge management for the workshop participants' purposes and identifying strategies to implement a successful knowledge management program across the national laboratories and at each individual laboratory. The workshop resulted in a set of recommendations for NNSA on practical steps it can take to promote safeguards knowledge management and retention within the DOE complex.

After the workshop introduction, the plenary discussed a definition of knowledge management to apply to the Office of International Nuclear Safeguards. It was agreed that the IAEA definition of knowledge management would fit the Office of International Nuclear Safeguards' needs, but it was necessary to define "specified objectives" for the Office of International Nuclear Safeguards to accompany this definition.

To define the specified objectives, the overall goal of the program was discussed and agreed on as follows:

Office of International Nuclear Safeguards goal for knowledge management in the U.S. international safeguards community is to identify and capture knowledge that can be shared and transferred across the community to foster collaboration, break down silos, and ensure the retention of important knowledge in order to ensure sustainability, gain efficiencies, and promote innovation.

Subsequently, the objectives to achieve this goal were defined as follows:

- Identify and prioritize what knowledge needs to be learned and retained.
- Capture knowledge so that it is available and accessible.
- Transfer knowledge.
- Encourage the use and integration of knowledge.

Once these objectives were defined, brainstorming sessions were conducted with the workshop participants to determine appropriate strategies for achieving each of these objectives.

Objective 1: Identify and prioritize what knowledge needs to be learned and retained

- Determine the best ways to prioritize safeguards knowledge for retention and transfer.
- Identify information to be captured for the DOE and national laboratory complex to access.
- Document lessons learned and update important documents.

Objective 2: Capture knowledge so that it is available and accessible

- Develop a safeguards knowledge repository to serve as a tool for national laboratories to access various reports.
- Promote the open sharing of data.

Objective 3: Transfer knowledge

- Share subject matter expertise across national laboratories.
- Engage retired SMEs for knowledge-sharing activities.
- Share instructional and outreach materials.

Objective 4: Encourage use and integration of knowledge

- Support integration of knowledge through a safeguards knowledge retention community of practice.

Since it is unlikely that each national laboratory could implement every strategy discussed, each laboratory was challenged to review the results of the workshop and develop a sustainable knowledge management strategy that will work for their laboratory.

Conclusion

The purpose of the Knowledge Management and Retention Working Group was to bring the national laboratories' different proposals on knowledge retention strategies together as part of a larger, complex-wide strategy. As laboratories undertook their projects, it became increasingly apparent that national laboratories face similar challenges with respect to identifying knowledge at risk of being lost and knowing what to do about it.

The laboratory-wide survey highlighted the fact that many formal and informal approaches are available to address the problem of knowledge retention, and that sharing these practices among national laboratories could go a long way toward supporting each laboratory in formulating their own strategy and helping to develop a complex-wide knowledge retention strategy. The culmination of the working group's collaboration was the Safeguards Knowledge Management and Retention Workshop, which brought together members of the knowledge retention working group, national laboratory representatives, and members of the parallel effort to building a safeguards knowledge repository. This workshop helped to further refine a knowledge retention strategy for the complex and was very much a community of practice in safeguards knowledge retention.

With this as a starting point, the working group members will continue their work by:

- Enhancing nonproliferationportal.com, a website containing nonproliferation information sponsored by the Office of International Nuclear Safeguards.
- Further developing the safeguards knowledge management and retention repository.
- Sharing laboratory-developed tools such as the workforce planning methodology and the workforce agility database within the safeguards community.
- Developing a sustainable knowledge management strategy at each laboratory.

Keywords

Knowledge management, knowledge retention, safeguards

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Bernadette Kirk worked for 36 years and was the director of the Radiation Safety Information Computational Center and a group leader in the Reactor and Nuclear Systems Division at Oak Ridge National Laboratory until her retirement in 2011. Kirk's nuclear research experience covers radiation transport using both Monte Carlo and discrete ordinates method and neutron diffusion theory. In 2013, she started her consulting business, Kirk Nuclear Information Services, which promotes collaboration between national laboratories and universities

Hannah Hale began supporting Oak Ridge National Laboratory's International Safeguards group of the Nuclear Security and Isotope Technology Division as a contractor in October 2015. Hale completed her master's degree in nuclear engineering in December 2015 and is currently pursuing a PhD in the UTK Bredesen Center for Interdisciplinary Research and Graduate Education's Energy Science and Engineering program with a focus in nuclear energy.

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Nuclear Forensics Education for Policy Students and Diplomats

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Abstract

This paper describes two nuclear forensic courses: a semester-length course used for policy students in a master's degree program in Nonproliferation and Terrorism at the Middlebury Institute of International Studies in Monterey, California; and a potential weekend program derived from the semester-long course. In discussing the courses, the article considers how to provide basic nuclear education to policy students and diplomats. Course overviews and syllabi are outlined, as are recommendations for a textbook and reading assignments.

Introduction

For the past 5 years, the author has taught a course in nuclear forensics to policy students in a master's program in Nonproliferation and Terrorism at the Middlebury Institute of International Studies (MIIS) in Monterey, California. Although nuclear forensics courses are taught at other institutions, the MIIS course appears to be the only one taught to nontechnical students. Most students in the course have little technical background with which to approach a course that can be very technical. What has been developed at Monterey is a course that is essentially a scientific language program, focusing on a goal of making students capable of knowledgeably discussing nuclear forensics with scientific and technical experts in the field. Students who have completed the course have in some instances been able to develop in positions of management where a knowledge of nuclear forensics is useful or even essential.

The author believes that most policy students have essentially the same educational background as diplomats and, therefore, the lessons learned also directly apply to the education of diplomats.

This paper will initially address the importance of policy students and diplomats having an understanding of not only the concepts of nuclear forensics, but the same level of technical language ability that students develop in the MIIS program. Should the world experience the detonation of an improvised nuclear device (IND), or the far more likely use of a radiological dispersal device (RDD), a basic knowledge of nuclear forensics to understand the event will be essential in many levels of government and in many agencies. Perhaps more important will be an understanding of the ability and limits of nuclear forensics to identify the event's perpetrators. To deal with these issues, diplomats and policy students who mature into decision-making positions need a basic understanding of the methods and language of nuclear forensics.

The subject of nuclear forensics can be parsed in a number of ways. By definition, nuclear forensics deals with both nuclear and other radioactive materials and the legal aspects of dealing with these materials in a forensic/criminal context. Other parsing can be to look at predetonation and postdetonation examination of materials used or resulting from an IND or RDD. From a forensics viewpoint, it is important to understand that nuclear forensics should be able to deal with both nuclear and other radioactive material to obtain forensic evidence, and should also have the capability to carry out conventional forensics on radioactive leak–contaminated items.

Crucial to the understanding of a diplomat or policy student dealing with nuclear forensics is knowledge about the international scheme of dealing with the issues, the times required to obtain various types of information, and the methods that scientists use to express the potential uncertainty of results. Unfortunately, a diplomat or policy student's knowledge of these issues may only become important when an actual incident occurs, and by then it may be too late to acquire the necessary understanding of the subject matter. Can this type of information be imparted to policy students in something other than a semester-long academic setting? The article proposes a truncated format and syllabus that could be taught to diplomats or policy students in a weekend-long workshop and a syllabus for a more traditional graduate-level program suitable for a university system.

Course and Text

At MIIS, Nuclear Forensics is taught as a four-unit course in a seminar format. Students are required to submit a semester paper of approximately 20 pages on a nuclear forensics topic of their choosing. The required text for the course is *Nuclear Forensic Analysis Second Edition.*[a] Although Moody is generally at too high a level for policy students, it is more or less standard in the field, and there does not appear to be an adequate alternative.[1] Students are advised that they may also use the first edition of Moody because the basic organization has not changed drastically. Reading assignments generally are from Moody and from sources available on the Internet or provided as PDF or Word files. Students are also required to use a basic scientific calculator, either a handheld device or one on their laptop or smartphone.

In managing the course, the author uses Dropbox for online storage of class materials. As will be noted, there are provisions for guest speakers and for the addition of topics of interest that come up during the semester. The final two class sessions are devoted primarily to student presentations on their paper topics. Table 1 provides a typical semester syllabus.

Table 1. Schedule and weekly assignments for the four-unit nuclear forensics course

Week 1	Topic: Course Introduction and Overview — What Is Nuclear Forensics? Assigned Reading: Moody Chapter 1; and Dunlop and Smith[2]. Both are available on Dropbox
Week 2	Topic: Nuclear Explosive Devices Assigned Reading: Moody Chapter 5; and IAEA Nuclear Security Series Publication No 2[3],
Week 3	Topic: Scientific Basis for Nuclear Forensics Assigned Reading: Moody Chapter 2
Week 4	Topic: Scientific Basis for Nuclear Forensics (continued) Assigned Reading: Moody Chapters 3 and 4
Week 5	Topic: Chronometry Assigned Reading: Moody Chapter 6
Week 6	Topic: Analysis Techniques Assigned Reading: Moody Chapters 7, 8, and 9
Week 7	Topic: Analysis Techniques (continued). Begin selection of paper topics for class presentation and final paper Assigned Reading: Moody Chapters 10 to 16
Week 8	Semester Break; No Class
Week 9	Topic: Analysis Techniques (continued) and Case Studies Assigned Reading: Moody Chapters 17 to 19 and begin 20 to 25
Week 10	Topic: Case Studies review for midterm examination Assigned Reading: Moody Chapters 20 to 25
Week 11	Midterm Examination (weeks 1–10) Topic: Possible FBI speaker via Skype (will be moved to an available date) Assigned Reading: Nuclear Forensics: Role, State of the Art, and Program Needs[4], will be posted in Dropbox. Joint Working Group of the American Physical Society and American Association for the Advancement of Science, also will be posted in Dropbox Topic: Review midterm, Nuclear Forensics on the International Scene (possible guest speaker)
Week 12	Assigned Reading: Kristo, M. J., D. K. Smith, S. Niemeyer, and G.B. Dudder.[5]
Week 13	Topic: To be determined Assigned Reading: none
Week 14	Topic: To be determined Assigned Reading: none
Week 15	Topic: Class presentation of projects Assigned Reading: none
Week 16	Class presentation of projects Assigned Reading: None Papers due

The goal at the completion of the course is for the students to have developed an understanding of the basic concepts of and equipment for nuclear forensics. They should understand the language of radioactive decay chains, chronometry, mass spectrometry, etc. By writing a focused paper on the topic of their choice, they should be able to demonstrate competency in command of the appropriate language.

Short Course or Workshop

Recognizing that not everyone — particularly diplomats — has the time to sit through a semester-long course on nuclear forensics, the author has considered developing a short course workshop. MIIS offers one-unit weekend workshops that typically run for three hours on Friday evening and then all day Saturday and Sunday. This schedule allows students to get a compressed look at a topic of interest. The MIIS workshops are taken for credit, and the workshop format could be applied for course credit, or a group or institution could issue a certificate indicating satisfactory participation in the workshop. Although no workshop on nuclear forensics has been taught to date, Table 2 presents the following concepts that would probably be the basis for a workshop syllabus.

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[a] Some may want to consider Fedchenko, V., ed. 2015. *The New Nuclear Forensics, Analysis of Nuclear Materials for Security Purposes*, Oxford University Press. United Kingdom. This book contains a chapter, "Destructive Forensic Analysis: Inorganic Mass Spectrometry," by K. Mayer, M. Wallenius, Z Varga, M. Hedberg, and N. Erdmann.

Table 2. Organization for a nuclear forensics weekend workshop

Day	Topics
Friday Evening	Introduction to the course Radiation Radiation detection Nuclear and other radioactive material Naturally occurring and man-made radionuclides Hands-on calculation of radioactive decay for common radionuclides International categorization schemes for nuclear and other radioactive materials
Saturday	Concepts of mass spectrometry Concepts of radiochemistry Concepts of attribution Introduction to basic types of mass spectrometry and radiation detectors Chronometry and examples of decay chains to date nuclear materials Importance of radiochemistry and the potential flow of nuclear forensic analysis
Sunday	Case study, such as the Bulgarian sample from Moody The Nuclear Forensics International Technical Working Group and national nuclear forensics laboratories Incidents of nuclear and radioactive material out of regulatory control Forensics aspects of evidence preservation and court testimony Considerations of time requirements for various attribution analysis tasks Consideration of a postdetonation analysis of debris from an IND

Conclusion

Education of nonproliferation policy students and diplomats in nuclear forensics is an important goal. Students often become program managers dealing with either direct management of forensics activities or become potential users of nuclear forensics information. Diplomats may need a basic understanding of nuclear forensics should they have to deal with a nuclear incident or accident. Experience has shown that the nontechnical policy students can learn the basics and language of the subject, and the author expects that diplomats (who generally have the same educational background of policy students he has taught) are also able to master the basics in a short-format course.

A semester syllabus has been outlined in this paper, along with a proposal for a short course (weekend workshop) on nuclear forensics. While the semester course is too time-consuming for a diplomat, the short course would be applicable to both diplomats and policy students.

Keywords

Nuclear forensics education, policy students, diplomats, syllabus, nonproliferation, terrorism

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Elements of a Sustainable Educational Experience in Nuclear Security and Safeguards

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Abstract

Over the past several years, Oregon State University's (OSU) School of Nuclear Science and Engineering (NSE) has partnered with the National Nuclear Security Administration and regional national laboratories to establish an academic emphasis in nuclear nonproliferation, safeguards, and security. OSU's recent efforts to strengthen this graduate emphasis are described, as are highlights of the entire educational experience at OSU, including didactic courses, online education, practical hands-on experience, extracurricular opportunities, and technical research specific to nuclear security and safeguards. Six graduate-level courses specific to nuclear security and nonproliferation education, including five new courses, have been formalized this year into the NSE curriculum. Efforts are currently under way to convert the course materials to align with the delivery format of OSU's top-ranked eCampus program and to integrate the courses into an optional focus for the online Masters of Health Physics degree. This article describes the courses and complementary extracurricular opportunities such as summer internships, practical hands-on training at the Volpentest Federal Training Center near Pacific Northwest National Laboratory, visits to international nuclear facilities to observe applied safeguards, and graduate research of relevance to the mission area. Collectively, the exposure to formalized coursework and real-life experience provides a promising avenue for developing a high-quality human resource capacity. The successes and lessons learned in establishing a graduate emphasis at a large, public university like OSU are discussed, along with particular challenges unique to top-tier research institutions. Ideas are presented from a university perspective on the sustainability of a formalized graduate emphasis in nuclear nonproliferation, safeguards, and security, with particular emphasis on success factors for students and faculty alike.

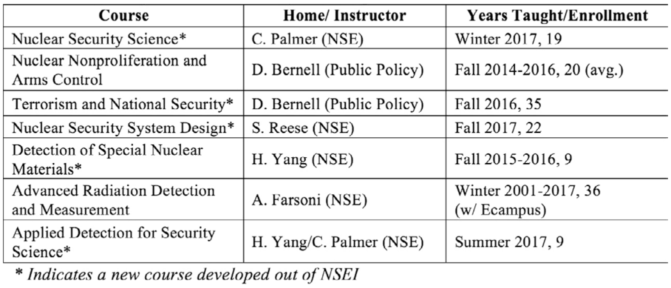
Introduction

It is apparent that the National Nuclear Security Administration (NNSA) is dedicated to the development of the next generation of nuclear security and safeguards professionals. Numerous offices within the NNSA demonstrate their commitment to education through programs such as the university consortia (NA-22), human capital development (HCD) of the Office of International Nuclear Safeguards (NA-241), and the independent curriculum development efforts of the Office of Radiological Security (NA-21). These programs are complemented by the NNSA nonproliferation graduate fellowship program and a range of internship opportunities at national laboratories. The School of Nuclear Science and Engineering (NSE) at Oregon State University (OSU) is engaged to some extent in all of these efforts and consequently has recently formalized a nuclear security educational track within the school.

The growth of a nuclear security and safeguards emphasis within NSE is viewed positively from the College of Engineering's perspective, as it aligns nicely with their mission "to transform lives and enhance society through impactful education and research." Still, the expectation from the college is that these efforts will be sustainable internally within the School of NSE by the standard metrics of academic success: supporting graduate student research, graduating students, and generating research products (i.e., journal publications, conference proceedings, and new technologies). Up to this point, OSU has been fortunate to have received support from NA-21 through an initiative that has directly contributed to curriculum development and course delivery, which is summarized below. Now it is time for NSE to consider how best, and to what extent, to maintain this effort such that it contributes to faculty and student success. This article discusses the elements of success from an academic perspective that allows for a sustainable educational emphasis in nuclear security and safeguards.

In 2016, NNSA's Office of Radiological Security approached OSU to evaluate curriculum developed out of their Nuclear Security Educational Initiative (NSEI) at Texas A&M University (TAMU). The evaluation compared course objectives and determined overlaps and gaps in the OSU course offerings and the NSEI course objectives. Measurable learning outcomes were outlined and aligned with course objectives already covered at OSU. The materials were organized into a smaller, module-based format that was more easily implemented in OSU's quarter-based academic calendar, as compared to the offerings at TAMU, which operates on a semester schedule. The outcome of this evaluation was the development of the five new courses outlined in Table 1, which complemented our existing courses. Collectively, these courses provide a comprehensive nuclear security and safeguards educational experience at OSU.[1]

Table 1. Summary of Nuclear Security and Nonproliferation Courses at OSU



Course	Home/ Instructor	Years Taught/Enrollment
Nuclear Security Science*	C. Palmer (NSE)	Winter 2017, 19
Nuclear Nonproliferation and Arms Control	D. Bernell (Public Policy)	Fall 2014-2016, 20 (avg.)
Terrorism and National Security*	D. Bernell (Public Policy)	Fall 2016, 35
Nuclear Security System Design*	S. Reese (NSE)	Fall 2017, 22
Detection of Special Nuclear Materials*	H. Yang (NSE)	Fall 2015-2016, 9
Advanced Radiation Detection and Measurement	A. Farsoni (NSE)	Winter 2001-2017, 36 (w/ Ecampus)
Applied Detection for Security Science*	H. Yang/C. Palmer (NSE)	Summer 2017, 9

** Indicates a new course developed out of NSEI*

Concurrent to the NA-21 effort, Pacific Northwest National Laboratory (PNNL) and the Office of International Nuclear Safeguards HCD have invested time and funding resources to provide subject matter experts for seminars and course instruction. For example, PNNL HCD has supported Ambassador Thomas Graham to contribute directly to the instruction of a Nuclear Nonproliferation and Arms Control course for several years. Additionally, an HCD-supported seminar within NSE draws an average of 40 students to discuss topics related to nonproliferation, arms control, and nuclear safeguards. This exposure to national laboratory employees is motiving to students who desire to make an impact by addressing international nonproliferation challenges.

Current Curricular Efforts and Challenges

The five new courses developed out of the NSEI were recently formally adopted into the NSE curriculum, with two of them cross-listed with Public Policy, encouraging a multidisciplinary experience. This process required the submission of a proposal with approvals from the NSE curriculum committee, the College of Engineering, and the Curriculum Council of OSU's Faculty Senate. The successful adoption of these courses now allows them to be listed in the OSU course catalog with a unique course number.

To capitalize on this course development, NA-21 is supporting NSE faculty to adapt the nuclear security (and safeguards) curriculum for online delivery to OSU's Extended Campus (eCampus). OSU has a long history of providing online education, and the School of NSE was one of the first at the university to offer a degree at a distance. For over a decade, the School of NSE has offered a Master's of Health Physics degree online via OSU's eCampus. The program consistently maintains course enrollments of more than 20 students, contributing to it being the largest health physics graduate program in the nation. The eCampus faculty and staff also research and implement the latest best practices for online delivery and have refined the style and quality of delivery. OSU's eCampus is now ranked in the top 10 online degree granting programs in the nation.[2]

While there appears to be desire and interest by faculty to teach these courses in future years, the primary challenges are the constraints on the number of faculty and instructional time. As will be discussed in defining academic success, instruction can often be undervalued when faculty are seeking tenure and other demands overshadow teaching. OSU's School of NSE has 10 tenure/tenure track faculty members, four full-time research faculty, and three additional instructors. The reality is that there is limited bandwidth of instructional resources, and long-standing, more traditional nuclear engineering courses tend to receive higher priority. Another complication is a new university budget model[3] that incentivizes large course sizes, making it more difficult to sustain specialized graduate courses.[4] The School of NSE administration is addressing these concerns by implementing a new teaching model that is intended to provide a mechanism to support the addition of a nuclear security and safeguards emphasis.

Extracurricular Activities

For a holistic experience in nuclear security and safeguards education, students at OSU are encouraged to engage in related opportunities outside of the classroom. Being in the same region as PNNL, OSU has natural ties with this national laboratory, which allows students to participate in PNNL Lab Days. Additionally, the Applied Detection for Nuclear Security is a hands-on course co-instructed by PNNL employees at the HAMMER Federal Training Center. This course exposes students to screening equipment and processes used for international nuclear security. Portable handheld detectors and portal monitors are used to provide direct experience with secondary inspection techniques. Additionally, this past summer, two graduate students and one faculty member traveled to Japan and the United Kingdom as a part of the NA-24 supported nuclear facility experiences tour.

In 2016, OSU successfully launched its first student chapter of the Institute for Nuclear Materials Management (INMM), which has drawn from the undergraduate and graduate student populations. Figure 1 displays photos from recent INMM events attended by OSU students. The chapter is building momentum and bringing exposure to nuclear security and safeguards within the School of NSE.

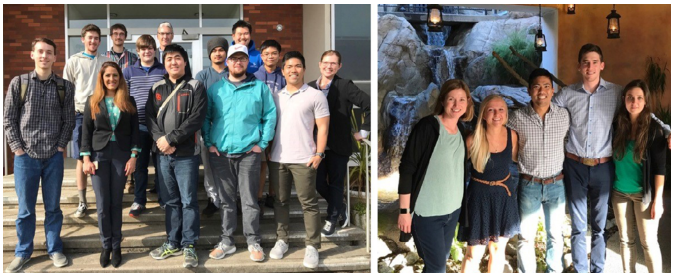


Figure 1. Photos of OSU's INMM Student Chapter members in Spring 2018 (left) and OSU student members attending the INMM 58th Annual Meeting in Indian Wells (right)

Elements of Success in Academics

Ideally, efforts that support the development of next-generation experts in nuclear security and safeguards benefit all parties: the sponsoring NNSA Office and lab partner and the academic unit within the university (NSE). Speaking from a university perspective, it is more challenging to define the specific benefits to the partnering labs. However, the assumed benefit is a supply of qualified and motivated graduates interested in contributing to the NNSA mission. To accomplish this, it is paramount that curriculum and experience(s) are provided to students so they can fully appreciate the relevant needs and professional opportunities.

An entirely academic experience is likely inadequate to inspire a career path. One approach to addressing this leans toward interacting with students directly by offering internships and fellowships. While internships and fellowships are of significant value to the student, the work may or may not align with their graduate research. There is also a possibility that directly funding students neglects the metrics that faculty need for professional advancement. Faculty are often willing to advise research projects that align with ongoing programmatic work at national laboratories; however, this often comes at a cost to the individual faculty advisor when financial support goes directly to the student. On the flip side, research funds that go to universities that are detached from programmatic efforts can be viewed as irrelevant and wasteful.

If national laboratories desire to engage students in research that can serve concomitantly as their academic research product (thesis), it is imperative that the project be truly collaborative between the national laboratory, faculty advisor, and student. For a graduate emphasis to be able to be sustained long-term, all parties involved must have a path that enables success from their point of view. So, while no specific solution is being proposed here, the objective is to better understand the issues at play so all parties can work toward a common goal of generating the next-generation experts in nuclear security and safeguards.

Successful Graduate Students

From a graduate student's perspective, success is likely defined as efficiently and affordably obtaining the education and skills necessary to acquire a degree and secure a professional position. Foundational to achieving this goal is the fundamental didactic coursework as well as a research project, both of which are necessary for a post-bachelor's degree. Coursework is a straightforward mechanism to transfer information and introduce relevant concepts. Research experience offers a deeper understanding of the issues, both technically and politically, beyond what is offered in courses. It also provides an opportunity to hone student problem-solving skills and refine their communication abilities.

While slightly oversimplified, Figure 2 illustrates that these key components of coursework and research cannot be viewed entirely independently. Coursework within an academic program must align to support the skills needed for research. Additionally, the existence of a productive research program generates resources, including instructional support needed to sustain curriculum delivery. The bullet points next to the research and courses components identify critical resources that need to be in place for those components to be accessible to the student. Clearly, instructional time and knowledgeable faculty are needed to offer the classes.

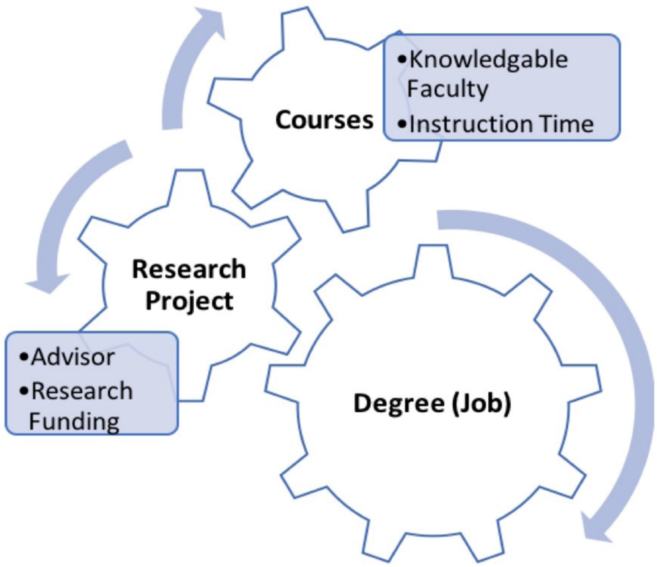


Figure 2. Key components of graduate student success

Also critical to the success of a student is the faculty advisor. For a student to successfully navigate graduate school, a faculty advisor is essential to ensure they are meeting the requirements for graduation, including coursework, exams, and research productivity. A faculty advisor also often serves as the student's connection to the real world and is abreast of opportunities for students to connect with national laboratories and/or other industry partners.

Traditionally, the faculty advisor also provides financial support to their advisees as research assistants. While limited funds exist within the university to pay students as teaching assistants for a year, at OSU it is expected that students seek out funded research opportunities with faculty by the second year of study. This arrangement is mutually beneficial to the student and faculty, providing the student with research experience, tuition coverage, and a graduate student stipend.

Several opportunities exist for students to receive research experience directly at national laboratories or in industry. At an undergraduate level, this serves the student well in obtaining a job by demonstrating real-life experience. While an internship can provide similar experience at the graduate level, the impact to the student is more complex. If a well-defined research project is introduced during the internship, it can spur collaboration and develop to serve as the student's academic research project. For this to be successful, it is vital to have buy-in by the faculty advisor (and committee members) and be accomplished in accordance with the university's academic process. From an academic perspective, this is a win-win scenario in which programmatic needs are being met and the student is progressing in their academic goals toward graduation. In this scenario, while success is being enabled in both the student and the lab partner, the faculty partner may not be integrated into the project in a manner that allows them to progress and meet their professional goals, which will be discussed later in the "Successful Faculty" section.

It is also possible that internships may negatively impact student progress toward their degree. There are occasions when students participate in summer research, and the appeal of securing a position outside of the university setting entices them into accepting long-term appointments. If this is done prematurely, it can significantly affect their ability to graduate in a timely manner. Although it is not formally studied, faculty approximate that off-site students nearly double their time to degree completion compared with students who stay on campus. Since the university requires continuous enrollment, this leads to increased cost of the degree and limits the student's professional opportunities as compared to graduating years earlier. In this case, while it is appealing to feel like the student is getting a jump start on their career, it may not in fact be in their best academic or professional interest. Also, due to the early physical separation from the academic advisor on campus, it can minimize the university's role in the research product, which directly affects faculty success and ultimately puts at risk the sustainability of the entire educational emphasis. If a student establishes an external collaboration, it is vital to integrate faculty into the research and find a mechanism to ensure the student achieves their academic goals in a timely manner.

Successful Faculty

A faculty advisor is integral to a graduate student's experience. Individual faculty research interests and their success are also important in establishing, nurturing, and preserving areas of emphasis within an academic unit. Although direct relationships between students and nonacademic institutions can prove valuable and successful, a healthy thriving academic emphasis requires faculty engagement. If this is accepted, then it is logical to conclude that it is also important for the faculty to be successful to sustain a graduate emphasis in nuclear security and safeguards.

A typical faculty member at a research university will divide their time among research, teaching, and service, with time allocated to each that varies based on academic field and institution. While all aspects of research, teaching, and service are valued at some level, it is well understood that universities are "constantly being challenged to improve research productivity and extramural funding activities of their faculty for economic reasons, particularly decreasing sources of state funding."[5,6]

An additional motivation for faculty to invest in research efforts (grant writing and establishing collaborations) is that their summer support is dependent on funded research activities. Acquiring sponsored research funding to support graduate students and faculty time, as well as producing research products such as peer-reviewed publications and conference proceedings, is central to faculty success. While teaching and service are necessary and enjoyable aspects of the job, it is often not as valued by university administration and is therefore not as heavily weighted in the promotion and tenure process. Coggburn, from North Carolina State University, and Neely, from University of South Florida, describe the situation:

> *Because research productivity is more visible than teaching-oriented outcomes, this push for higher standards has tended to shift the focus of academic departments disproportionately toward research in the appraisal of faculty performance. … Consequently, the importance of teaching and community service in professional performance evaluation (such as tenure and promotion standards) has been diminished, crowded out in many instances by a "publish or perish" mentality. The end result of this shift has often been a reduction in the time and effort faculty members dedicate to other professional functions, such as teaching, advising, and community service.*[7]

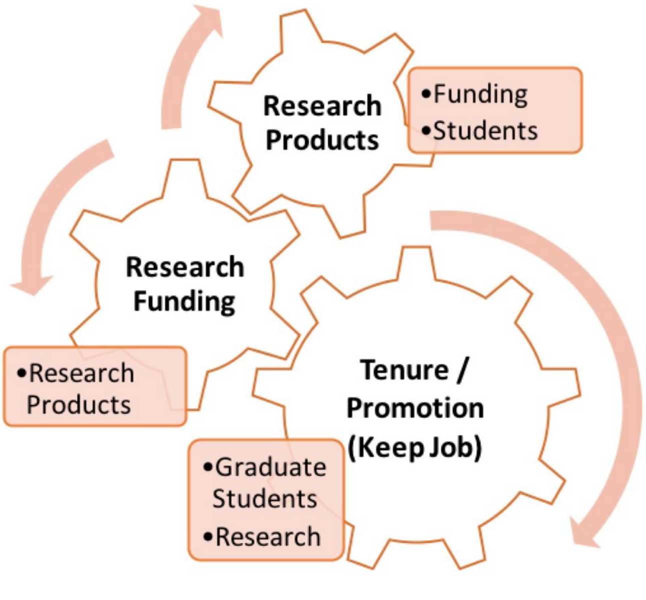


Figure 3. Key components of success for faculty at research institutions

According to OSU's College of Engineering, $55.6 million of sponsored research was awarded in the 2016–2017 fiscal year to their 182 tenure/tenure track faculty, an average of more than $300,000 per faculty member.[8] The expectation of research productivity is foundational to ensuring faculty success. Figure 3 illustrates how these key components of research products and research funding are interdependent and drive the faculty member toward academic success at a research institution.

Also of note are the resources needed for each driving research component to be achieved. While a startup package of support is typically offered to incoming faculty, the expectation is that an equilibrium will be established whereby research products, such as publications and the development of new technologies, provide a basis to become more effective at bringing in research funding. These products are also dependent on the ability to financially support and advise graduate students to assist in the funded research, making the research funding also necessary to generate research products. It is an interdependent cycle, which when smoothly functioning, results in successful faculty and students.

Research Funding

Obtaining funding at research institutions typically includes responding to open and competitive calls announced on grants.gov. Grants.gov serves as a centralized location to search for federally funded opportunities that tend to be highly competitive and time-consuming with a relatively low success rate. Exclusive pursuit of this route of funding can be so time-consuming to faculty that it can be detrimental. Regardless, it is important for universities to have connections to national laboratories because collaborations are often encouraged. Successful university-led awards can also indirectly support collaborative research at national laboratories. Lab collaborations can also work well when lab-directed research contracts flow to universities to support student and faculty time. These tend to be relatively small efforts with a well-defined scope of work and deliverables. If these types of contracts can also serve as student research, this is an example of how both laboratories and universities (students and faculty) all accomplish their respective goals.

The primary mechanism for funding research at universities specific to the mission of the NNSA is through NA-22's university consortia. This model provides a long-term (5-year) investment into a multiuniversity collaboration that supports a common mission. With no direct experience, these appear to be productive collaborations that support students and faculty and prepare students for careers in nuclear nonproliferation. A 5-year commitment also offers stability for faculty and students to focus on research, potentially increasing research productivity by relieving faculty from a constant proposal-generating state. However, if faculty are not participants of the consortia, there are very limited opportunities available in nuclear security or safeguards-related research. Since research is central to faculty and student success at universities, this model creates a barrier for new or small programs to grow and thrive in nuclear security and safeguards.

Conclusions

Over the past several years, notable progress has been made at OSU to establish and grow an academic experience emphasizing nuclear security and safeguards. These efforts include expanding and formalizing a curriculum that covers a spectrum of nuclear security topics and providing student experience outside of the classroom. Yet, to sustain a formalized educational emphasis in nuclear security and safeguards in practice, long-term success of both students and faculty must be considered. Aspects of graduate student success and faculty success were outlined with the conclusion that funded and productive research is central to a thriving and holistic academic emphasis at a research institution. While programmatic laboratory-directed collaborations with students and faculty are common, both positive and negative aspects of how these collaborations are realized have been discussed, as well as their impact on the various parties. The objective of this article is not to prescribe one optimal approach but to offer a student and faculty perspective of success so the community better understands what is required to sustain a positive and productive educational emphasis. It sets the foundation for a continued discussion on how laboratory partners and universities can move forward together to educate and prepare the future generation for careers in nuclear security and safeguards.

"Coming together is a beginning, staying together is progress, and working together is success." — **Henry Ford**

Keywords

University curriculum, nonproliferation, successful graduate program

Author Biography

Dr. Camille Palmer is an associate professor in the School of Nuclear Science and Engineering at Oregon State University. Her professional interests emphasize international nuclear security and nonproliferation, in which areas she collaborates with Oregon State University's School of Public Policy. Prior to academics, she was a staff member in the Thermonuclear Applications and Foreign and Improvised Nuclear Design groups at Los Alamos National Laboratory. She has also supported the sustainment of the Minuteman III delivery systems as a systems engineer with the Northrop Grumman Corporation. Camille holds a PhD in nuclear and radiological engineering from the University of Cincinnati.

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Utilizing Distributional Measurements of Material Characteristics from SEM Images for Inverse Prediction

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Abstract

The U.S. Government has been conducting actinide material processing experiments with the goal of identifying processing signatures of nuclear forensic value. Valuable signatures have the ability to credibly predict the source characteristics of material. In the search for potential signatures, a large amount of effort is invested in gathering detailed scanning electron microscope (SEM) images of processed material with a subsequent analysis of particle measurements using image analysis software, such as Morphological Analysis of Materials (MAMA). Based on many measured particles, the software calculates many distributional characteristics of particles, including the perimeter, vector area, etc. Often, each distribution is summarized as a mean and standard deviation for use in the prediction of source characteristics. However, distributional measurements contain a wealth of information such as distributional shape and skewness, which can provide meaningful information in discriminating source characteristics. To this end, methods using the entire distribution of measurements are being developed. Leveraging statistical functional regression approaches for entire distributions improves the prediction of source characteristics over the traditional approach of using simple summaries. The methodology is demonstrated with data from a bench-scale uranium study.

Introduction

Experiments are being conducted at U.S. national laboratories for research in nuclear forensics. These experiments are used to explore the impact of different production and processing parameters on characteristics of the materials produced. The goal is to build fundamental understanding of the robustness of the processes, as well as to develop models from which interdicted materials can be traced to their original production environments. The ability to examine the chemical and morphological characteristics of the material and connect it to settings used during production can be related to solving what is often referred to as an inverse problem or the calibration problem in the fields of applied mathematics and statistics.[1,2,3,4] In an inverse problem, the goal is to infer unknown factors X from measured observables Y. In nuclear forensics, which is a particular instance of the inverse problem, X can represent source characteristics, such as material origin and production parameters of interdicted special nuclear material. Y is the analytical measurements taken from the material, representing a potential nuclear signature. Beyond nuclear forensics, inverse prediction is used widely within the more general forensics field,[5] computer modeling,[6,7] chemometrics,[8] nutrition tracking,[9] and geosciences.[10,11]

To understand and distinguish between aspects of the morphological characteristics from different samples, scanning electron microscope (SEM) images are used. The software package Morphological Analysis of Materials (MAMA)[12,13] is being used to assist in calculating many distributional characteristics of measured particles. These distributional characteristics include area, perimeter, and shape. Figure 1 shows one SEM image with particle segmentation completed by MAMA. The particles included in the distributional morphological summaries are outlined and shaded in blue.

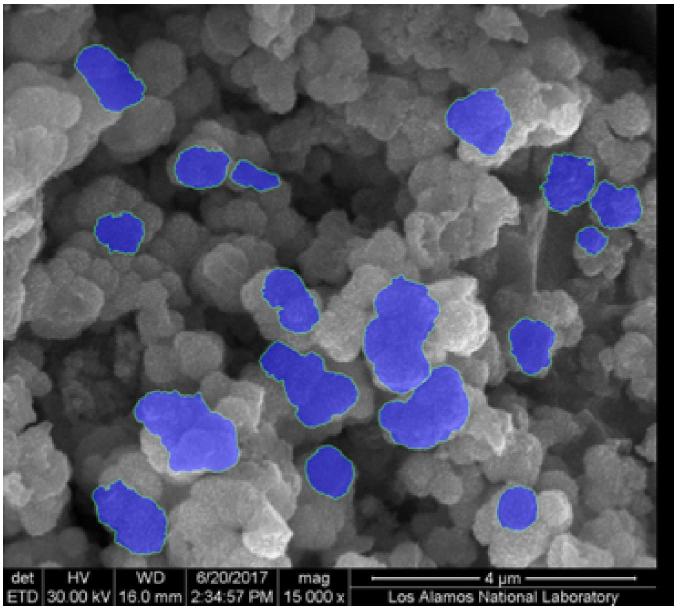

Figure 1. SEM image from MAMA software. The blue shapes are the particles from which measurements such as vector area and pixel area are calculated.

Recent efforts have been made to use the particle distributions obtained from such image segmentation for nuclear forensics. For example, Olsen et al.[14] use hypothesis testing to test for differences in distributions of particle characteristics of U_3O_8 calcined at varying temperatures. Prediction of calcination temperature classes using advanced machine learning techniques applied directly to SEM images has also shown promise.[15] When inferring multivariate processing conditions, methods of inverse prediction using scalar measurements are well developed. For example, Thomas et al.[2] and Lewis et al.[16] review the statistical technique of building a forward model for each of the scalar measurements as a function of the multivariate processing conditions. The collection of forward models is then inverted to produce predictions of the processing conditions. To use these techniques when faced with distributions of particle characteristics, the common practice is to summarize the distributions with a set of scalar values, like the mean and set of quantiles. The response surfaces are then developed on these scalar summaries. The goal of the statistical methods presented in this paper is to demonstrate how examining the entire distribution of these morphological characteristics can be advantageous compared to just looking at simple summaries, such as the average, for distinguishing between the different samples of an experiment. The distribution contains information about what ranges of values are expected, as well as the center, spread, and skewness of the distribution. The authors consider data from a bench-scale ammonium diuranate experiment to illustrate the method and how it is able to extract key distinguishing characteristics of the distribution.

The paper is organized as follows. First, a description of the bench-scale ammonium diuranate data on which methods are tested is described. Next, a mathematical description of inverse prediction is described in the setting with scalar responses to set the stage for use of distributional responses. Functional data analysis is then briefly described, followed by a detailed description of the functional inverse prediction methods used in this paper. A short simulation study demonstrating the potential of functional inverse prediction is provided. Next, these methods are applied to the bench-scale uranium study. The concluding section reviews the advantages of this approach and includes some discussion.

Bench-Scale Data

The bench-scale ammonium diuranate experiment manipulated five production factors: the ratio of uranium to 8M HNO_3 (at three levels: 50, 100, and 200 mg/mL), the stir rate (170, 280, and 400 rpm), the flow rate for metered delivery of the NH_4OH (2.5, 5.0, and 7.5 mL/min), temperature (21.5°C, 35°C, and 50°C), and the ending pH (5, 8, and 10.5). The ranges of each of these factors were selected to produce ammonium diuranate materials of suitable quality for its intended use. Because resources — and hence the available size of the experiment — were constrained, a statistically designed I-optimal experiment[13] (p. 470) was conducted. I-optimal designs seek to minimize the average prediction variance of responses throughout the input region of interest and provide practical designs when the goal is inverse prediction.[17,18] The design assumed a model with all main effects and two-factor interaction terms. Main effects are the effects of changing the level of each factor individually on the response, and two-factor interactions are the effects of changing the levels of two factors at a time on the response. The total number of runs was 21, with the experiment run sequentially. Three initial runs were conducted to verify equipment and process setup. The next 15 runs represent the core of the experiment, with three follow-up runs at the conclusion of the experiment to be used as a form of cross-validation to compare results and predictions against the original model based on the first 18 runs. Figure 2 shows the five factor combinations selected for the I-optimal design for the three stages of the experiment, with the design providing good coverage of the input combinations throughout the design space. The three columns distinguish among three temperature settings, and the three rows of ending pH levels distinguish among the three levels of pH that were chosen in the bench-scale experiment. The *x, y, and z* axes in each of the row-and-column combinations of temperature and ending pH distinguish between each of the three levels of U:HNO_3, stir rate, and flow rate.

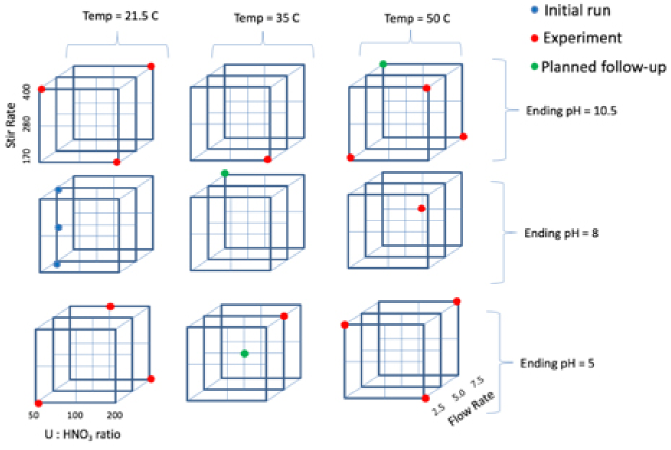

Figure 2. Factor combination for the ammonium diuranate I-optimal design based on three initial pilot runs. Colors indicate the order in which the experimental runs were conducted.

Particles were segmented with MAMA software to identify distinct particles that could be appropriately measured. For each experimental run, 5–10 mg of material was mounted on an adhesive carbon tape applied to a 12.7 mm aluminum SEM pin mount, and two areas were imaged. For each of the two chosen areas on the tape, four images were taken from each slide with magnifications of 5000x, 10,000x, 15,000x, and 25,000x. All particles that could be segmented from the image were used, with some images not yielding any particles of the appropriate size described in the MAMA documentation.[19] The image shown in Figure 1 is at 15,000x. From the collection of eight available images for each experimental run, between 6 and 120 particles were measured. Table 1 shows the number of particles for each of the 18 experimental runs. For each of the particles, 14 morphological characteristics were measured. These included multiple measurements of area (vector based, convex hull, and pixel based), perimeter, and shape.

Table 1. Number of particles analyzed for each of the 18 experimental runs.

Run	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
N_i	120	93	100	57	45	33	67	26	20	20	56	66	33	55	38	42	6	48

Inverse Prediction

Statistically, the goal of inverse prediction is to estimate an unknown p-dimensional set of source characteristics, or inputs X^*, that most likely produced a new observation with measured responses, Y^*. Often, the source characteristics consist of p scalar inputs, i.e., $X^*=(x_1^*,x_2^*,\ldots,x_p^*)^T$. Likewise, the measured responses consist of q scalar values, i.e., $Y^*=(y_1^*,y_2^*,\ldots,y_q^*)^T$. Both Thomas et al.[2] and Lewis et al.[16] discuss statistical methods for inverse prediction in this setting. For example, the common statistical linear regression model can be used to estimate model parameters and then can predict the response measurements given the input variables. Given a new observation with unknown inputs, these fitted models can be inverted to estimate the inputs.

For example, Figure 3 plots the mean response for each run against the stir rate on the left and the flow rate on the right for several of the responses. The linear least squares fit through the data (blue), and a 95 percent confidence band (gray) is shown. A moderate relationship between the three responses shown and the stir rate (since some of the lines are not horizontal) exists, whereas no significant relationship between flow rate and the responses appears to exist (since the lines are nearly horizontal). However, using simple summaries of these distributions neglects the wealth of information available from using the entire distribution of measurements, such as skewness or distributional shape.

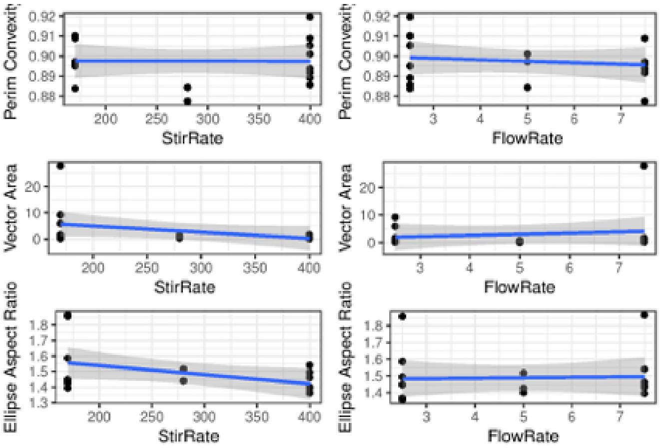

Figure 3. Plots of mean response by run against the stir rate on the left and the flow rate on the right. Linear least squares fit overlaid with confidence band. A stronger relationship appears to exist between responses and the stir rate than with the flow rate.

Functional Data Analysis

Functional data analysis (FDA) is a branch of statistics that considers analyzing data that are functional in nature. An example of functional data is the temperatures at a given location over time. Although the temperature is generally recorded only at discrete time points, in principle it could be evaluated at any time. Data from multiple locations could be considered as a collection of time series functions of temperatures plotted versus time. Similar to any other branch of statistics, FDA has several goals, which include (but are not limited to) visualizing the data in easily understandable formats, communicating patterns and relationships among or between variables, and understanding the variation in the data. Many in-depth references cover the rich aspects of FDA.[20,21,22,23]

Leveraging FDA approaches for detailed distributional information improves the prediction capability of source characteristics over the traditional approaches of using simple summaries. Additionally, inverse prediction typically requires that the number of responses is at least as large as the number of input factors considered in the experiment. This is required for unique identifiability of the best set of input levels for a given new observation. FDA shows potential that this requirement can be relaxed, and a smaller number of responses are often able to predict the best set of input levels.

Methods

The new statistical methods discussed in this section extend existing inverse prediction approaches to include situations where some or all of the individual response measurements are not scalar, but distributional. Because multiple particles are measured for each experimental run, the collection of measured values allows empirical estimation of the distribution of the response. The distribution provides a rich set of information for inverse prediction beyond raw summaries like the mean and standard deviation. The following subsections provide information on how the distributional response data are formed for each experimental run, and a summary of functional inverse regression.

Distributional Response Data

In the bench-scale data, 18 experimental runs with different settings for the explanatory variables were manipulated during the experiment. For each run, SEM images are produced, segmented, and analyzed using the MAMA software, resulting in measurements of characteristics of the particles within the produced sample. For a single characteristic, such as vector area, the collection of measurements constitutes an empirical estimate of the distribution that is characteristic within the sample. By ordering the observed values from smallest to largest and plotting them versus the quantiles of the empirical distribution with values of $(1/N_i, 2/N_i, \ldots, N_i/N_i)$, where N_i is the number of observed particles for sample *i*, the cumulative distribution function (CDF) can be approximated. Different experimental settings are expected to produce material with different properties that could manifest themselves in distinct patterns in these distributions.

From a statistical analysis perspective, it is important to account for all aspects of the distribution when building models to predict source characteristics (i.e., experimental settings) from measured responses. To achieve this, the estimated CDF of the distribution is used within the FDA framework as a response in a functional linear regression (see the “Functional Inverse Regression” section).

A common alternative to using the entire distribution is to summarize the distribution with a finite number of summary statistics, such as a measure of the center of the distribution, like the mean or median, and its spread with the standard deviation. These scalar summaries could be used as responses in inverse prediction models.[2,16] However, reducing to summary statistics risks losing important information not captured by just these aspects of the distribution. In the case of means and standard deviations, information regarding the shape of the distribution is lost. Such information could prove more powerful for inverse prediction. In the simulation study section, the most extreme example is explored using synthetic data, wherein each response distribution has exactly same mean but with distinct differences in the shape determined by the input variables.

In more general cases, still more information in the response distributions exists than in a collection of summary statistics. This paper aims to demonstrate that distributions can be used with functional regression techniques to inform inverse prediction of source characteristics. The results often have the potential to be more precise and accurate than traditional inverse prediction methods that use only scalar responses. Thus, the distributional responses can be more powerful at performing inverse regression due to the increase in information. In addition to being more powerful, the potential to use fewer response variables shows potential. This would enable a smaller subset of responses to distinguish effectively between input settings than using the scalar approaches, thereby reducing the burden of data collection and measurement. In traditional inverse regression, one must have $q \geq p$ in order to have unique predictions to predict x for a given set of responses y. This can quickly become a burden if there are many experimental conditions of interest. When using distributional response data with FDA, this constraint can potentially be relaxed.

Functional Inverse Regression

This section briefly introduces the proposed inverse regression method using the full distributional data instead of summary statistics, or the aggregate method. Interested readers should consult Ramsay et al.[20] for a thorough introduction to FDA and functional regression. The functional inverse regression procedure explained in this section requires two forward modeling steps. First, (1) fit a functional model to the discrete response data, and (2) fit a functional regression with the model from (1) and experimental factors as covariates. Then, use an optimization procedure to perform inverse prediction using the estimated parameter regression from (2).

Functional model for distributional data

The conversion of distributional data into functional data used for inverse regression is described here. Let Y_{ij} be a vector of observations from experimental run $i = 1, \ldots, n$ and response variable $j = 1, \ldots, q$ of length N_i corresponding to the vector of experimental conditions X_i. Because we want to compare distributions of responses, we compare the CDF of responses. The CDF of a univariate random variable Z is defined as $F_Z(t) = P(Z \leq t)$ and completely characterizes its distribution. The first step is to estimate the CDF of Y_{ij}. This is done with the empirical cumulative distribution function (ECDF) of Y_{ij},

$$V_{ij}(t) \equiv \hat{F}_{Y_{ij}}(t) = \frac{1}{\mathrm{N_i}} \sum_{k=1}^{N_i} \mathrm{I}(Y_{ijk} \leq t) \tag{1}$$

where Y_{ijk} represents the kth element in Y_{ij}, t is the index for the CDF of Y_{ij}, and I() is the indicator function. This produces a step function, but a smooth function can be interpolated at any value of t needed for FDA. The larger the number of observations within an experimental run, the smoother the curve will become. An additional advantage of using a spline to summarize each of the curves is that it allows for more straightforward comparisons between results for samples with different numbers of observations. Fitting a cubic b-spline using squared error loss and the ECDF, V_{ij} as the response:

$$V_{ij}(t) = \alpha B(t) + \delta_{ij}(t), \tag{2}$$

achieves this, where $B(t)$ is a b-spline basis matrix that is constructed according to De Boor[24], α is the set of spline parameters, and $\delta_{ij}(t)$ is a mean zero error term. Estimation of α is done as a constrained regression linear programming problem. To ensure the b-spline conforms to a CDF, the estimation procedure is constrained such that $\alpha B(t)$ is nondecreasing and between 0 and 1. The CDF of Y_{ij} is then estimated as:

$$W_{ij}(t) \equiv \widehat{V_{ij}}(t) = \hat{\alpha} B(t). \tag{3}$$

The smooth function $W_{ij}(t)$ gives a unique representation of the distributional response for each experimental run i and response variable j, which the authors consider to be the response function.

Functional Regression

Functional regression has many of the same ideas as standard linear regression, but it has response variables in the form of functions instead of scalars. Because the responses are functions, the regression parameters are also functions. The functional regression model is:

$$W_{ij}(t) = \boldsymbol{X}_i' \boldsymbol{\beta}_j(t) + \epsilon_{ij}(t), \tag{4}$$

where the regression coefficients $\boldsymbol{\beta}_j(t)$ are functions of t and $\boldsymbol{\epsilon}_{ij}(t)$ is a mean zero, stationary stochastic process.[24] Estimation of the regression parameter functions proceeds similarly as the standard linear regression procedure. However, $W_{ij}(t)$ is evaluated at many values of *t*, and ordinary least squares estimation is performed at each *t* to get estimates of β. Many different interpolation methods can be used to see the functional forms of $\widehat{\boldsymbol{\beta}_j}(t)$.

Inverse Prediction

Given estimates of regression parameter functions $\beta(t)$ under model (4), inverse prediction of X_i proceeds similarly to the standard scalar case. To predict the explanatory variables given $\widehat{\boldsymbol{\beta}_j}(t)$, $j = 1, \ldots, q$ and new functional observations Y_{ij}^*, we compute its CDF $W_{ij}(t)^*$ as described in the "Functional Model for Distributional Data " section, and perform the following optimization for X_i:

$$\widehat{\boldsymbol{X}_i} = \arg\min_{\boldsymbol{X}_i} \textstyle\sum_{j=1}^{q} \int \left| \widehat{W_{ij}}(t) - W_{ij}(t)^* \right| dt, \tag{5}$$

$$\widehat{W_{ij}}(t) = \boldsymbol{X}_i' \widehat{\boldsymbol{\beta}_j}(t). \tag{6}$$

In practice, the integral in (5) is approximated with a sum over a discrete number of values of *t*. Note, the restriction in the previous case where we require $q \geq p$ to ensure a unique solution is less restrictive for functional forms. Since the response now has higher dimension, $W_{ij}(t)$ can be evaluated at a large number of values of t. This means we can evaluate $W_{ij}(t)$ for at least p values of *t* for *p* unknowns. The authors acknowledge that there is not infinite information in $W_{ij}(t)$. Thus, producing a diagnostic evaluating an equivalent form of the degrees of freedom approach (evaluating the *q* and *p* constraints) to quantify that amount of available information in the functional form is a future area of research.

Analysis

The predictive ability of the statistical methods discussed in the previous section are applied to a simulation study and the bench-scale uranium data. Both demonstrate the abundance of information that is contained within distributions.

Simulation Study

To assess the predictive ability of this method, a simulation study is performed. The goals for this study are threefold: (1) to compare the predictive abilities of the methods described in this paper to the aggregate method; (2) to compare predictive abilities when $q = 1$ and $q = 2$; and (3) to compare predictive abilities for different values of *n* (number of experimental runs), *N* (number of observations per experimental run), and correlations between response variables. Without loss of generality, the authors assume that all sets of observations for given experimental run and response are equal and set $N = N_i$. Response data are simulated from the following simple linear regression model:

$$Y_{ij} = \boldsymbol{\beta}_j x_i + \boldsymbol{\epsilon}_{ij} \tag{7}$$

The authors simulate the explanatory variables x_i from a Uniform(0,10) distribution. Values of β_1 and β_2 were simulated jointly from a bivariate normal with zero mean vector, standard deviation 1 and correlation ρ, $N(\mathbf{0},\Sigma(\rho))$. Each component of Y_{ij} has uniquely simulated $\boldsymbol{\beta}$ values. The error terms $\boldsymbol{\epsilon}_{ij}$ are simulated such that $\mathrm{cor}(\boldsymbol{\epsilon}_{ijk},\boldsymbol{\epsilon}(_{ij'k})) = \rho$ and are otherwise uncorrelated. In this simulation, we consider all combinations of $n = 50$ and 100, $N = 50$ and 100, and $\rho = (-0.9, -0.6, -0.3, 0, 0.3, 0.6$, and $0.9)$. In each case, a second data set is simulated to calculate prediction mean squared error (PMSE) to evaluate predictive power in inverse prediction. PMSE is a standard measure of predictive power, but other summaries of prediction exist, and other options, such as mean absolute deviation, could have been used. Figure 4 shows the ECDFs for all *n* response vectors from one simulated data set. The coloring indicates the value of x_i, which highlights a clear relationship between x_i and the ECDF that can be extracted using the functional inverse method. Note how the centers of all of the lines are grouped together to match the requirement that the means of the responses were generated from a source with a fixed mean. Figure 5 plots the observed sample mean of each response vector Y_{ij} against its value of x_i, which shows there is no relationship in the mean, but there is an increase in the variability as x_i increases. The aggregate method would perform linear regression on the data in Figure 5 and would result in a slope estimate close to 0, rendering inverse prediction unhelpful for discriminating between x_i values, since this is necessary for inverse prediction.

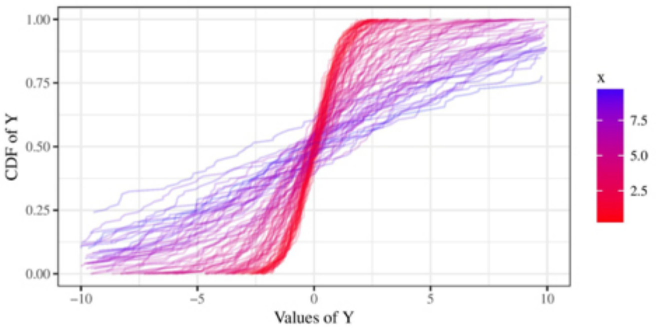

Figure 4. Empirical CDFs of Y for one simulated data set each with n = N = 100 and $\rho = 0.6$. The color of each line corresponds to its respective x_i value.

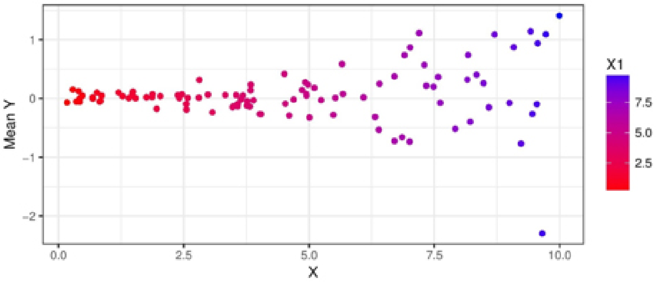

Figure 5. Mean of each of the observed vector Y_{ij} plotted against x for one simulated data set.

The results of the simulation study (Figure 6) shows that the PMSE decreases considerably for the two plots in all cases when *n* increases from 50 to 100, where *n* is the number of response functions, or number of experimental runs. Conversely, the number of observations within a run, *N*, does not have much effect on predictive power when it is increased from 50 to 100. This is not surprising since CDFs tend to be smooth, well-behaved functions. A b-spline with a low number of knots is able to capture its shape with a small amount of data. It is clear that using two response variables (*q*=2) rather than only one (*q*=1) provides additional benefit. If the two response variables had correlation of –1 or 1, the PMSE would be the same as the $q = 1$ case because there is no new information in the second response. Note that ρ is not equal to the correlation between Y_{i1} and Y_{i2}, but the parameter used to simulate the data. For perspective, the variance of the *Uniform*(0,10) distribution is 8.33, an order of magnitude larger than the PMSEs from the functional inverse method. The PMSE from the $n = N = 100$, $q = 1$, $\rho = 0.6$ case using the aggregate method is 18.1, which suggests the functional inverse method can be significantly better at inverse prediction.

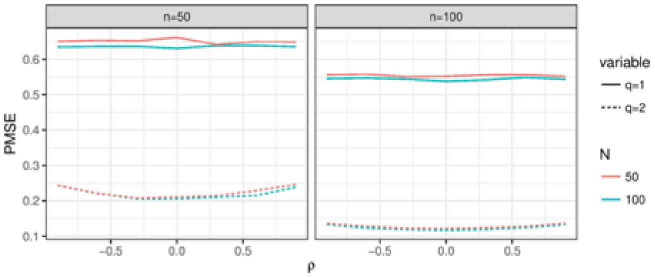

Figure 6. PMSE of functional inverse prediction for x for all levels of ρ, n, N, and q.

Bench-Scale Uranium Data

In this section, inverse predictions using the functional data and the aggregate methods are made using experimental uranium bench-scale data as previously described. The bench-scale data have observations from 18 experimental runs, with five explanatory variables. Those variables are U:HNO_3 ratio, stir rate, flow rate, end pH, and temperature. For each experimental run, eight SEM images are taken across four magnifications and analyzed using the MAMA software. The number of measured particles from each run is obtained from all usable particles from the eight images. The following measurements are taken for each image: vector area, convex hull area, pixel area, vector perimeter, convex hull perimeter, ellipse perimeter, electrical critical dimension (ECD), major ellipse, minor ellipse, ellipse aspect ratio, diameter aspect ratio, circularity, perimeter convexity, and area convexity. Since many of these response variables measure similar characteristics of the particles (but in different ways), several of the responses are highly intercorrelated. Three groupings of responses have high intragroup correlation: area/perimeter measurements, aspect ratios, and convexity. Little information is added by using multiple responses from each group since there is very high correlation within each of these groups. If inverse prediction is desired for each of the five explanatory variables, one must have $q \geq p$ to use the aggregate method. Three and one response(s) for the functional method are also considered here.

The five response variables were chosen by selecting one from each of the three categories described above, and then two more were selected that were a combination of lower correlation with other response variables and high correlation with the explanatory variables. The five responses used were vector area, ECD, ellipse aspect ratio, perimeter convexity, and area convexity. The subset of three responses is the vector area, ellipse aspect ratio, and perimeter convexity, and the one used is the vector area. Figure 7 plots ECDFs for the three response variables grouped by experimental run colored according to the stir rate on the left and the flow rate on the right. There is noticeable grouping by stir rate for the log vector area, whereas for the flow rate, there is less systematic pattern and it looks like a random scatter. This is the type of feature the functional inverse model can take advantage of in the case of the stir rate, and in the case of the flow rate, it will likely give similar results as the aggregate method.

One particle from one of the experimental runs was missing some of the response data. For simplicity, this particle was removed because the authors believe it has little impact on the outcomes. The number of knots used for the b-spline to fit CDFs is capped at two, because the authors are using cubic splines with an intercept term and run 17 has only six observations. As discussed in the "Simulation Study" section, the small number of observations should not be a problem due to the smooth behavior of CDFs. A look at the empirical CDFs of all the responses for these data confirm this as reasonable.

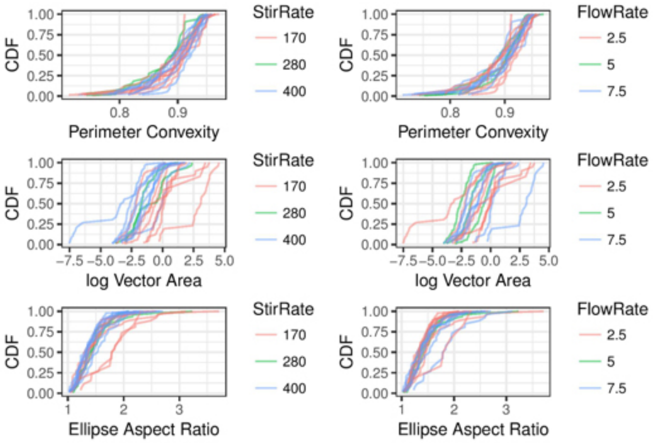

Figure 7. Empirical CDFs for three response variables grouped by experimental run colored according to stir rate on left and flow rate on right. There is noticeable grouping by the stir rate for the log vector area, whereas for the flow rate, it looks like a random scatter.

Leave-one-out cross-validation (LOOCV) is used to assess the predictive performances of the aggregate and functional methods for the 18 experimental runs. LOOCV was used because predictions beyond the observed data were desired, but the small sample size is restrictive for using a training and testing set of data. For each iteration of LOOCV, the aggregate model and functional model were fit using the remaining 17 runs of data. Root PMSE is used as the measure of predictive performance. Table 2 shows Root PMSE on the scale of the data for all four models considered. The functional inverse method predicts better than the aggregate method for all explanatory variables except for U:HNO$_3$, for which the results are comparable. This result is consistent even when only one response variable is used for the functional method. These results help show there is an abundance of information in the distributional responses, even when it is not visually apparent when using the aggregate method (Figure 7).

Table 2. Root PMSE results of LOOCV for uranium bench-scale data using aggregate and functional inverse methods on the original scale. The aggregate method was fit using five response variables; the functional method was fit using five, three, and one response variable.

	U:HNO$_3$ Ratio	Stir Rate	Flow Rate	End pH	Temperature
Aggregate-5 Y	83.31	135.70	3.67	3.72	19.74
Functional-5 Y	79.35	81.53	3.42	2.65	16.89
Functional-3 Y	84.84	84.28	3.33	2.71	16.64
Functional-1 Y	76.99	85.30	3.37	2.79	16.41

Discussion

This paper presents a new approach for inverse prediction of source characteristics of nuclear material. SEM images with multiple particles provide the basis for constructing ECDFs from which forensic information can be gathered. However, all this information corresponds to one set of experimental conditions; it is common to simply aggregate all the data for a given response within a SEM image. A new approach for inverse prediction uses all the data for each measured morphological characteristic from SEM images, rather than simply aggregating the distributional data by experimental run. By treating the response data functionally, the authors can perform regression on those estimated functions rather than aggregated scalars with this analysis technique. Because distributions are more than their means, this approach considers the relationships in the spread and shape of the distributions, which provides further ability to distinguish response distributions for different values of explanatory variables.

In the simulation study constructed with nearly equivalent mean effects, the functional inverse method can still find signal in the response data, since the distribution of the response varies in terms of higher-order moments than simply the mean. The simulation results showed a significant improvement in PMSE over the aggregation method when there is little differentiation in the means. Additionally, the study helps show the relative effects of sample size in terms of number of experimental runs, as well as number of observations per run. The number of observations per run does not appear to make a meaningful difference between $N = 50$ and $N = 100$, which is likely due to the smoothness of CDFs. A real data example using uranium bench-scale data also shows the ability of the functional inverse method to predict better than the aggregate method for almost all explanatory variables. Additionally, the improved predictive ability of the functional inverse method still holds when using fewer response variables than explanatory variables ($q < p$). This supports the argument that higher predictive power can be achieved using fewer response variables than a number of explanatory variables. Thus, data collection could be streamlined and simplified. This is apparent by the number of correlated response variables, yet at least p is needed with the aggregate method even if little additional information is gained from the extra variables.

Although the methods presented in this paper make comparisons to simple linear models, the functional inverse method can be extended to allow for more complicated models that include higher-order coefficients and interactions. Additionally, the gains in predictive performance in the uranium bench-scale example are a noticeable improvement over the current inverse prediction methods. The authors understand in some cases, like flow rate, the prediction error is still moderately large. On the other hand, the predictions for stir rate and end pH dropped below one standard deviation using the method described in this paper. It is important to note that the example presented was based on a small sample size of 18 for this method. The simulation study shows that with moderately larger sample sizes, this method can become quite powerful in performing inverse prediction. This, along with the moderate improvements in the real data example, showcases the potential for using entire distributional measurements.

Keywords

Inverse regression, functional analysis, ammonium diuranate, scanning electron microscope images, morphology

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Adah Zhang is a statistician in the Statistical Sciences Group at Sandia National Laboratories. She received her MS in biostatistics from Case Western Reserve University in Cleveland, Ohio. Her master's degree work involved working with large cancer databases, specifically with brain tumors. At Sandia, Zhang supports a variety of engineering projects through data visualization, analysis, modeling, and simulation. Additional statistical methodologies used include FDA, uncertainty quantification, quantification of margins and uncertainties, and reliability.

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Marianne Wilkerson joined Los Alamos National Laboratory as a technical staff member in the Chemistry Division in 2002. She received her PhD in inorganic chemistry from the University of New Mexico-Albuquerque in 2000, and she was a postdoctoral research associate at Los Alamos National Laboratory. Her research interests include applications of chemistry-based techniques to forensic and nonproliferation problems, optical spectroscopy of 5*f* orbital-occupied actinide species, use of synchrotron experiments for understanding actinide bonding, and chemical synthesis of actinide compounds in aqueous and nonaqueous media.

Gregory L. Wagner earned his BS and, subsequently, an MS in microbiology at North Carolina State University. He is currently a research technologist in the Physical Chemistry and Spectroscopy Group in the Chemistry Division at Los Alamos National Laboratory. Previously, he spent 3 years as a microbiology instructor at Virginia Polytechnic Institute and State University. During Wagner's 20 years at the laboratory, he has focused on a wide variety of national security concerns of a microbial and chemical nature. Recent work has emphasized the controlled synthesis of nuclear materials and identifying discrete chemical signatures of these materials.

Julie Gravelle is a chemistry student at Miami University. She served as a Domestic Nuclear Defense Laboratory intern at Los Alamos National Laboratory in 2017.

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Application of a Triple Bubbler Sensor for Determining the Density, Surface Tension, and Depth in Molten Salts

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Abstract

A novel triple bubbler sensor developed at the Idaho National Laboratory has been applied to high-temperature molten salts used in pyroprocessing of spent nuclear fuel to aid in nuclear material accountancy and process monitoring. In pyroprocessing, special nuclear materials accumulate in the electrorefiner salt. The concentration of the salt can be monitored using destructive and nondestructive analysis techniques. To calculate the mass of special nuclear materials in the electrorefiner vessel, the salt volume is needed in addition to the concentrations. Determining the salt volume in the electrorefiner is daunting as the density of the salt as well as the depth is difficult, if not impossible, to measure accurately with current techniques. The triple bubbler sensor has the ability to determine the density, surface tension, and depth in *situ* using a maximum bubble technique. This is significant as it provides a means to determine the salt volume and special nuclear material mass in the electrorefiner vessel in a timely manner. In this current work, the sensor was tested in two different molten salts for calibration and validation of the bubbler and approach. In LiCl-KCl, the calibration was performed using density and surface tension while the depth (partial validation) was determined to within approximately 0.4 percent. A second salt mixture (CsCl-LiCl) was used to further validate the calibration and approach. In these experiments, the accuracies were approximately 0.4 percent, 18 percent, and 0.8 percent for density, surface tension, and depth, respectively. This study has successfully demonstrated that the triple bubbler sensor can be used to accurately (below 1 percent uncertainty) determine molten salt density and depth.

Introduction

Electrochemical (i.e., pyroprocessing) technology is being widely studied throughout the world as a potential alternative to aqueous reprocessing of spent nuclear fuel (SNF). Central to this process is the electrorefiner (ER), in which the useful uranium in the SNF is electrochemically transported through a molten salt electrolyte to a cathode for later recovery.[1] As part of this process, uranium, plutonium, and other actinides accumulate in the ER salt over time. The material accountancy and safeguards of these special nuclear material buildups in near real time are a significant challenge due to the elevated processing temperatures, remote operation within a hot cell, and high radiation fields. Analytical techniques outside of the hot cell can be used to provide the special nuclear material concentrations of salt samples from the ER. However, determining the actual mass of these materials in the ER presents a significant challenge because the density and volume of the salt within the vessel is largely unknown. Kim et al. have explored a bubbler type instrument to measure down to the top surface of the salt with reasonable results (within 1.1 percent)[2]. The Idaho National Laboratory (INL) recently developed a triple bubbler sensor capable of determining the density, surface tension, and depth of a fluid in near real time and has tested it in aqueous fluids.[3] These experiments in aqueous media have shown that the sensor can determine the density, surface tension, and depth with accuracies on the order of 0.2 percent. This current work aims to test the sensor in several different molten salt media to further test and validate the triple bubbler. The approach is to perform experiments in LiCl-KCl eutectic and CsCl-LiCl eutectic salts in the temperature range between 450°C and 525°C. Several tests conducted in the LiCl-KCl salt will be used to calibrate the sensor, and the remaining tests will be used to validate the calibration.

Methods

An illustration of the triple bubbler is shown in Figure 1. The probe consists of three (labeled in the figure) Kovar metal bubbler tubes supported by a stainless steel shroud. The lengths of the three tubes are 54.28 cm, 54.38 cm, and 44.11 cm for tubes 1, 2, and 3, respectively. The radii of the tubes are 2.27 mm, 1.27 mm, and 2.29 mm, for tubes 1, 2, and 3, respectively. The pressure measured using tubes 1 and 3 can be used to calculate the density of the fluid as shown below:

$$\rho = C_P \frac{P_1 - P_3}{g \Delta x} \qquad (1)$$

where C*p* is the density correction factor, *ρ* is the density, *P* represents the measured pressures (subscript represents the tube number), *g* is the gravitational constant, and *Δx* is the vertical distance between the tips of tube 1 and tube 3. Using formulas from tubes 1 and 2, the surface tension can be calculated using the following expression:

$$\gamma = \alpha \frac{P_2 - P_1 + 0.69 r_1 g \rho}{1000} \qquad (2)$$

where r_1 is the tube radius of tube 1, γ is the surface tension, *α* is the surface tension correction factor, and 1,000 represents a conversion from mN/m to N/m. The depth of the fluid is then calculated using:

$$d = \frac{P_1 - P_B}{g\, \rho} \qquad (3)$$

$$P_B = \frac{2}{3} \rho g r_1 + \frac{2\gamma}{r_1} \qquad (4)$$

$$D = d + j_1 \qquad (5)$$

where *d* is the depth from the bubbler tip to the top surface, P_B is the excess bubble pressure, *D* is the total depth, and j_1 is the distance between the bottom of tube 1 and the bottom of the crucible. Details of the derivation of the above expressions can be found in Williams et al.[3]

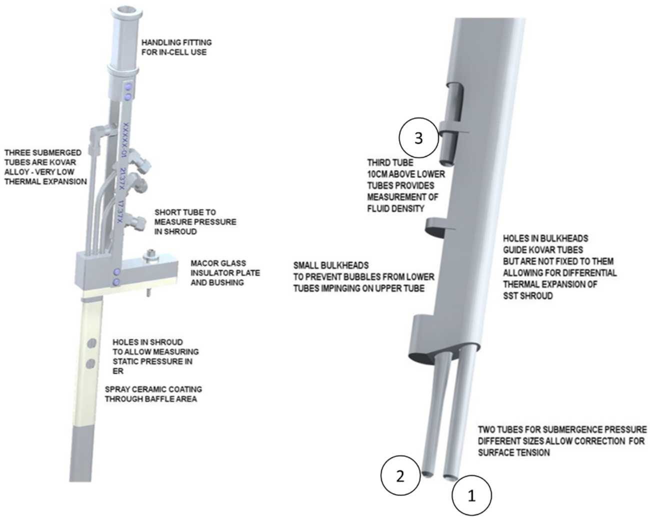

Figure 1. Illustrations of the triple bubbler sensor: (left) the top portion of the triple bubbler sensor, and (right) the lower portion of the sensor showing the tube numbering.

The experimental equipment is shown in Figure 2. A two-zone crystal growing furnace (OXY-GON, Inc.) was used and has two 30-cm heating zones that can be maintained at independent temperatures. The furnace cavity is an alumina retort tube that is connected to an inert gas atmosphere system (vacuum system with argon gas hookups). A stainless steel cap was designed to seal the retort tube while providing inserts/ports for the triple bubbler, thermocouple, argon gas inlet/outlets, and a conductivity depth probe. The thermocouple used had 12 thermocouple leads positioned every 2 inches (~50 mm) from the bottom.

Figure 2. Photo of the two-zone furnace including the bubbler control panel.

To independently measure the depth of the molten salt, a conductivity probe approach was used. In this approach, a wire-wrapped quartz rod connected to a 600-mm digital height gauge (Mitutoyo 570-314) was lowered into the retort tube. The wire on the rod was connected to a light-emitting diode (LED) sensor whose other lead was connected to the thermocouple immersed in the salt. When the quartz rod (wire tip) came in contact with the top liquid surface, the circuit was completed (via electrical conductance through the salt) and the LED illuminated. To measure the salt depths, the conductivity probe was zeroed at the top of the retort cap (representing the bottom of the bubbler support/top of the bubbler tubes) prior to being lowered into the retort. The distance to the salt level (d_1) was measured prior to plunging the probe into the salt where the depth from the reference to the bottom of the crucible (d_2) was measured.

The salts studied in this setup were LiCl-KCl (44 wt% LiCl, 56 wt% KCl) and CsCl-LiCl (73.16 wt% CsCl, 26.84 wt% LiCl). These salts were prepared in an inert atmosphere glove box. The crucible used to contain the salts was 316 stainless steel that was 30 cm tall with an inside diameter of 60.2 mm. Following the salt weighing, the crucible was covered and transferred from the glove box into the furnace retort. The cap was then placed and a vacuum was drawn followed by backfilling with argon gas. This vacuum/backfill process was repeated approximately 10 times over a period of two hours while ramping up and maintaining a temperature of 200°C. Once the salt had melted, the bubbler was lowered into the retort (with the bubbler gas on) to a position just above the salt to pre-heat. During this phase and while the bubbler was within the retort, argon gas was purged into the retort system at 3 L/min. After approximately 20 minutes of pre-heating, the bubbler was lowered into the salt.

The temperature range for these experiments was between 450°C and 525°C in the salt bath. Argon gas controlled by the instrument panel was bubbled through the molten salt and the bubble pressures were recorded using a LabVIEW interface. At each temperature, a total of four to five replicate measurements were made. At the start of each replicate, d_1 and d_2 were measured (six replicates each) as well as the temperature profile of the bubbler/system. After these measurements were recorded, the bubbler system recorded at least 10 minutes of pressure data (approximately 300 bubbles). Following the pressure measurements, the depths and temperature profile were again recorded. This procedure provided before and after depth measurements and temperature profiles for every bubbler measurement replicate.

Results and Discussions

An example of the measured pressure profiles is shown in Figure 3. From the profiles, the peak pressures were determined using the "findpeaks" function in the commercial software MATLAB. Over the 10-minute acquisition, there was some bubble interference, which created outliers in the data. To identify and eliminate these outliers, a built-in boxplot function in MATLAB was used. Following outlier removal, the peak pressures were averaged and the standard deviations determined. In this way, each replicate had a single representative pressure value.

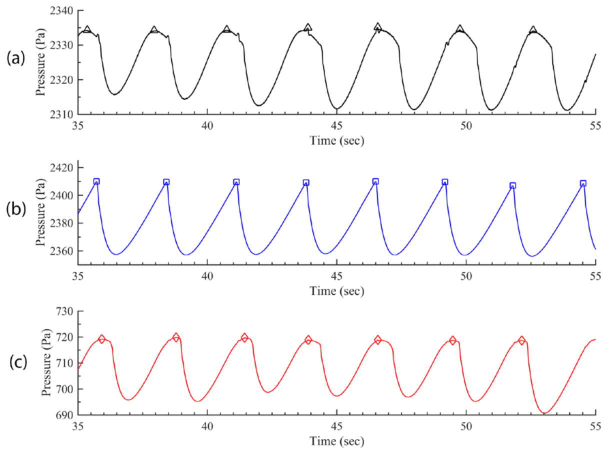

Figure 3. An example of measured pressure profiles; (a) tube 1, (b) tube 2, and (c) tube 3. Data were taken in LiCl-KCl salt at 500°C.

The experimental data were split into calibration and validation data sets. The calibration set consisted of the pressure data collected during the LiCl-KCl experiments at all temperatures. The validation set included the depth measurements from the LiCl-KCl experiments as well as all of the data collected (pressures and depths) during the CsCl-LiCl experiments. For calibration, the known density and surface tension values as determined in the literature[4] were used with Equations 1 and 2 to solve for C_p and α. In the calibration, the density and surface tension values as reported by Janz[4] were selected because they have been more commonly cited. Table 1 shows the resulting calibration factors at the different temperatures. For both the density and surface tension, the corrections are relatively constant with temperature, with the largest deviation being observed at 525°C. Being that the differences were small between temperatures, representative values for C_p and α were obtained by averaging over the different temperatures. This resulted in a C_p of 1.0015 ± 0.0020 and an α of 1.261 ± 0.028.

Table 1. Calibration constants as a function of temperature

T (°C)	C_p	A
456.4	1.0015 ± 0.0018	1.260 ± 0.026
475.7	1.0012 ± 0.0022	1.260 ± 0.035
505.2	1.0019 ± 0.0020	1.260 ± 0.022
524.7	1.0015 ± 0.0022	1.264 ± 0.029
Average	1.0015 ± 0.0020	1.261 ± 0.028
Std	0.0002	0.005

As the independent depth measurements were not used as part of the calibration, they can be used to support the validation of the approach. Table 2 shows the measured depth (contact sensor) as well as the calculated depth of the fluid using Equations 3 through 5 in the LiCl-KCl salt. The residual between the measured and calculated depths vary from 0.33 mm (0.22 percent) to 0.59 mm (0.39 percent). The density and surface tension values as calculated using the averaged C_p and α are also shown in Table 2 and were compared to the literature values. The uncertainties for density were determined using the propagation of errors from P_1, P_2, Δx, and C_p, where Δx is a function of the tube lengths, d_2, and thermal expansion (10 percent). The uncertainties in the surface tension were determined using propagation of errors of P_1, P_2, r_1, α, and ρ. The uncertainties of the depth were determined from propagation of errors from P_2, ρ, γ, r_1, and j_1.

Table 2. Bubbler calculations for the fluid density, surface tension, and depth in LiCl-KCl eutectic salt. Included is the depth of the fluid as measured using the contact sensor and the percent difference between the measured and calculated depths.

T (°C)	ρ (kg/m^3, Bubbler)	ρ kg/m3, [4])	γ (mN/m, Bubbler)	γ (mN/m, [4])	Measured Depth (mm)	Calculated Depth (mm)	% Diff.
456.4	1644.4 ± 1.4	1644.3	129.9 ± 1.9	129.5	148.56 ± 0.04	148.2 ± 0.4	0.22
475.7	1634.3 ± 1.5	1634.2	128.2 ± 2.0	127.9	149.26 ± 0.05	148.9 ± 0.5	0.27
505.2	1618.1 ± 1.7	1618.6	125.9 ± 2.1	125.5	150.33 ± 0.05	149.8 ± 0.5	0.36
524.7	1608.4 ± 1.7	1608.3	123.9 ± 2.4	123.9	151.42 ± 0.04	150.8 ± 0.5	0.39

The data collected from the CsCl-LiCl experiments were also analyzed using the determined calibration coefficients as part of the validation. Several literature findings for CsCl-LiCl were identified that could be compared to the triple bubbler calculations. Ito and Hasegawa[6] experimentally determined the density of CsCl-LiCl eutectic (59.3 mol% LiCl) salt below the temperature of 400°C. No additional property correlations (density and surface tension) for eutectic CsCl-LiCl were directly available. However, Janz[4] had density and surface tension correlations for 55 mol% LiCl-CsCl and 70 mol% LiCl-CsCl within the temperature range between 577°C and 761°C. An approximation of the density and surface tension at 59.3 mol% was achieved by interpolating between the 55 and 70 mol% correlations. Then by extrapolation, the density and surface tension were determined in the temperature range of interest. For density, the comparison between Ito and Hasegawa and the interpolated and extrapolated Janz data was approximately 1.5 percent.

The values for density and surface tension as calculated using the triple bubbler and the literature correlations are shown in Table 3. For density, the percent differences between the values reported by Ito and Hasegawa[6] and the bubbler were below 1.4 percent and below 0.4 percent between Janz[4] and the bubbler derived-value. For surface tension, the percent difference was approximately 18 percent. The large difference between the expected surface tension and the calculated value may be the result of the extrapolation of the literature values or impurities in the experimental salt. An alternative possibility is that the correction factor for surface tension in CsCl-LiCl varies from the calibration salt (LiCl-KCl). Previous experience[3] in aqueous media showed little variation in the correction factors through multiple fluids (large range of densities and surface tensions), and it is assumed that the calibration factors would be similar between these two salts. However, insufficient data are available from the current experiments and literature to determine the exact source of the discrepancy. As the surface tension is needed in the depth calculation, large inaccuracies will contribute to the overall error. The surface tension uncertainties (shown in Table 3) contributes to approximately 0.2 mm of uncertainty in the depth calculations (based on propagation of error). At 18 percent uncertainty in surface tension, the surface tension contribution to the depth uncertainty is approximately 1.2 mm.

Table 3. CsCl-LiCl salt properties as a function of temperature as calculated from the bubbler data and literature sources

T (°C)	ρ (kg/m^3, [6])	ρ (kg/m^3, [4])	ρ (kg/m^3, Bubbler)	γ (mN/m, [4])	γ (mN/m, Bubbler)
422.5	2450.92	2420.11	2428.1 ± 6.0	109.22	131.0 ± 3.6
456.6	2426.30	2391.83	2399.7 ± 6.1	106.63	124.4 ± 4.5
476.8	2411.68	2375.04	2382.9 ± 6.3	105.10	123.7 ± 3.3
498.7	2395.87	2356.88	2364.7 ± 6.5	103.42	122.0 ± 3.2
523.6	2377.94	2336.29	2343.8 ± 6.6	101.53	122.1 ± 3.8

A comparison of the calculated and independently measured salt depths is shown in Table 4 for CsCl-LiCl salt measurements. The residual between the depth measurements was between 0.52 mm and 1.24 mm. The differences were between 0.35 and 0.82 percent, which is below the targeted 1 percent accuracy for safeguards measurements. The depth uncertainties as shown in Table 4 were determined using surface tension uncertainties of about 3.6 percent (as reported in Table 3), and the depth uncertainties (about 0.5 mm) were approximately 0.33 percent of the total measurement. If the 18 percent surface tension uncertainties were used in the calculation, the depth uncertainty would be approximately 0.93 percent of the total measurement. In either case, the uncertainty is acceptable (less than 1 percent) for the depth. Clearly, any improvement on the surface tension contribution will improve the overall depth uncertainties.

Table 4. Comparison between the CsCl-LiCl salt depths as determined using a contact sensor and the bubbler. Units are in mm.

T (°C)	D (Measured)	D (Bubbler)	Residual	% diff.
422.5	149.06 ± 0.10	148.5 ± 0.4	0.52	0.35
456.6	151.59 ± 0.10	150.7 ± 0.4	0.88	0.58
476.8	152.45 ± 0.12	151.2 ± 0.4	1.24	0.82
498.7	152.94 ± 0.10	151.8 ± 0.4	1.12	0.73
523.6	154.09 ± 0.11	153.0 ± 0.5	1.12	0.73

Conclusion

Experiments were performed in LiCl-KCl eutectic salt. Calibration factors were 1.0015 and 1.261 for density and surface tension, respectively. For density, the accuracy in the validation salt (CsCl-LiCl) was within approximately 0.4 percent. For surface tension, a discrepancy of up to 18 percent between the calculated and the literature values were identified. The exact cause of this discrepancy is unknown but may be the result of salt impurities, inaccurate literature data, or variation in the calibration factor between salts. The depths of the salt in the test vessel were determined to within 0.4 percent in a LiCl- KCl salt and approximately 0.8 percent in a CsCl-LiCl salt. These results indicate that the triple bubbler sensor has the potential to accurately and precisely (both within 1 percent) determine the density and depth of the ER salt in near real time. The triple bubbler sensor designed at INL can significantly enhance the material accountancy, safeguards, and process monitoring of the electrochemical processing of SNF.

Keywords

Safeguards, maximum bubble pressure, density, surface tension, pyroprocessing

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Book Review

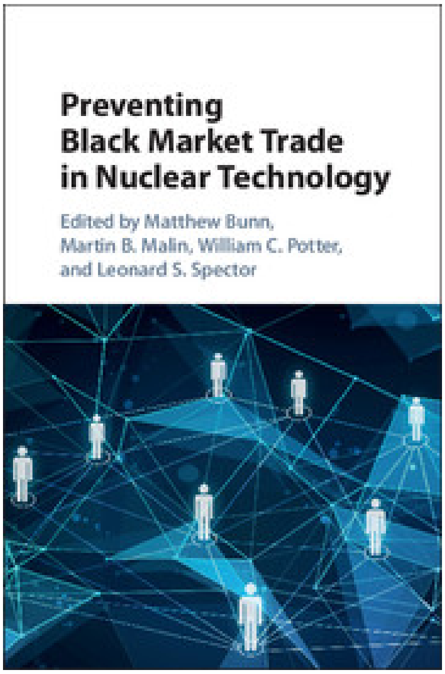
Mark L. Maiello, PhD
Book Review Editor

Preventing Black-Market Trade in Nuclear Technology

Matthew Bunn, Martin B. Malin, William C. Potter, Leonard S. Spector, Editors
Hardcover, 374 pages, ISBN 978-1-107-16376-8
Cambridge University Press, New York, NY 10006, 2018

Diplomacy and policy making may get all the attention when it comes to non-proliferation policy-making, but one aspect of the overall effort is carried out silently and in a largely uncoordinated fashion by law enforcement, international inspections, UN sanctions, financial sector restrictions and other interventions. The initiative includes those who work in export control that ask the questions and apply the brakes to prevent, or slow the acquisition of materials and equipment that could be used in an illicit effort to build nuclear weapons.

This book is a behind-the-scenes look at a black market that trades money for nuclear equipment and the counter-effort to halt these attempts. Largely a story originating with United Nations Resolution 1540 that requires nations signing on to create effective export controls, it is also a story about how these controls affect the free trade that now dominates the world economy. The mission of the controls: prevent single and "dual-use" materials from being acquired by nations bent on covertly achieving a platform to build nuclear weapons.



Preventing Black-Market Trade in Nuclear Technology is an ensemble effort using four editors and twelve other contributors. Such a large team allows for a wide breath of coverage. Chapters review the roles of the various components of black-market control such as intelligence, sanctions, law-enforcement, and financial constraints. Introductory chapters on the intricacies of illicit trade and its present and future landscape help ease the reader into the discussion. Later chapters cover filling the gaps in the field. The reader will find information on defeating black-market networks and initiating new, innovative ideas to combat illicit procurement. The last chapter is a summary by the editors summarizing the progress in the field, the gaps that require repair and future progress necessary to improve the counter-initiatives.

Although all the contributions are thorough treatments of their subjects, there are a few standout chapters – those that in particular, indicate the wide sweep of the book. For example, Chapter 11 is an interesting review of the Russian effort to stop black market networks. Though somewhat self-promoting, it does give an assessment of past and current Russian export control programs and its associated work especially with reference to the illicit nuclear program of Iran. A Russian view of international sanctions supports the discussion. That being said, a similar chapter on Pakistan's work in the field - assuming that was possible – could have been ever so more impactful.

Matthew Bunn, one of the co-editors contributed to three chapters, one of which focuses on strengthening nonproliferation culture. The cultures referred to are those of private sector companies including their subsidiaries, research universities, and government laboratories doing work on or with nuclear technology. Each is a unique entity requiring distinctive approaches to countering black market activities. Consider the myriad number of private firms that produce single or dual use equipment and their production of materials that go into equipment such as centrifuges. Some are large firms that have the resources to train and bake in a non-proliferation agenda into their employees. Others are much smaller and therefore will have greater difficulty not only recognizing the need for concern about black market activities but will find implementation of an internal nonproliferation program daunting. Even international corporations are challenged in this area because they must reach into foreign offices and subsidiaries where the cultures have been home grown and set in place for long periods of time.

John Park, Leonard Spector and Ian Stewart have composed an interesting chapter on new initiatives to combat the illicit procurement of nuclear technology. The analysis includes the problems associated with thwarting the North Korean and Iranian programs. Solutions include circumventing the Chinese middlemen who have facilitated North Korean acquisition of nuclear equipment by paying these middlemen monetary rewards for exposing North Korean acquisition attempts. Another is to make a robust, concerted effort to retrieve illicitly acquired equipment from violating nations. This has heretofore not been done systematically. The latter could involve the Nuclear Suppliers Group, the International Atomic Energy Agency and the United Nations through its Security Council Resolutions. The private sector supply chain alluded to above can also be turned from an apparent liability into an asset. A "Good Practices for Corporate Standards" can be found in Annex A to this chapter. Here, eight principles that companies can adopt are outlined that support nonproliferation efforts.

The editors deliver a powerful concluding chapter that reviews the counter-capabilities relevant to each area previously covered: intelligence, law-enforcement, sanctions, export controls, private sector responsibilities, financial controls, international organizations and organizational culture change. Each is assessed for accomplishments and each receives a gap analysis with proposals for improvement. Probably the most telling assessment of the current collective black market counter-effort can be found here. As the editors write, had the A. Q. Khan network reawakened after falling asleep in 2000, they would find a much different landscape in which to operate. An astonishing array of obstacles comprised of organizations, policies, rules and norms now is in place. The efforts of intelligence organizations, law enforcement and the banking system that admittedly are far from perfect, have forced black market conspirators to devise innovative means to work around these counter-operations. One concludes that progress to slow or prevent black market procurement has come very far since 2000 but because the enemy did not cease efforts, more must be done to improve the chances of interdiction. The editors do not disappoint here. They identify important gaps such as the poor communications between stakeholders with much to gain from a strong proliferation regime such as the intelligence organizations, the international financial sector and law enforcement, all of which have legitimate issues regarding the free sharing of information. Another concern discussed is the variation in the interpretation of potentially illicit procurement requests among various sectors of the counter-effort. They are to be specific, not based on a common standard. Alarm bells sounding in the banking sector do not necessarily set them off in the law enforcement regime. Such inconsistency speaks to the uncoordinated nature of the counter effort.

Despite the recommendations for improvement made in the Park, Spector, Stewart chapter, the editors supply their own unique solutions in the finale. Their effort here is practical, concrete, and (to the untrained mind – my own) eminently possible – assuming of course, the international and national political will exists to implement them. Recommendations such as the creation of a committee of industry nonproliferation consultants to advise governments and international organizations like the IAEA on the success or failure of current export controls and updating the illicit procurement strategies being used by black market participants, does not seem that difficult to do.

This book is systematic, comprehensive, and detailed. It is well edited with little redundancy unless required to drive home a point. If it doesn't fill a gap in the literature about non-proliferation, it surely is an exhaustive update about black market activities. Its use as a teaching tool or as a supplemental text in the classroom is advised. As a reference and self-teaching tool, it also appears to be an excellent choice.

No doubt will remain that the largely silent army fending off proliferative black market efforts – disparate, uncoordinated, and spread amongst several sectors of the economy and that do not necessarily have non-proliferation as a primary goal or even understand it properly, has despite its flaws, proven to be a deterrent to black market activity. That said, like many human endeavors, the editors and contributors make it plain that it can stand improvement.

Unlike many human endeavors, ignoring the call to improve these efforts could prove catastrophic.

Taking the Long View in a Time of Great Uncertainty
60 Years in the Making

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


INSTITUTE OF NUCLEAR MATERIALS MANAGEMENT

60th ANNUAL MEETING

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CELEBRATING 60 YEARS

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Like many organizations across the world that became engaged in "things nuclear" at the beginning of the nuclear age, the INMM is celebrating a decadal anniversary - its 60th year in 2019 as a leading international professional society for the stewardship of nuclear materials and related technologies to enhance global security. In Palm Desert, California, this next July, we will also be celebrating our 60th Annual Meeting.[1] One of those "other" organizations the Institute has worked with since its early beginnings is the International Atomic Energy Agency (IAEA). The IAEA was established as an autonomous organization on July 29, 1957, through its own international treaty, and reports to both the United Nations General Assembly and Security Council. The collaboration between the INMM and its members over the decades with the IAEA has helped to create a future that benefits from nuclear energy.[2] Just as the 60th IAEA General Conference was held in 2016,[3] and that Institution celebrated their decades-long history of successes, it behooves our membership to reflect back on the scientific, technological and policy challenges that have arisen in these past decades, and what the Institute has succeeded in accomplishing as a member of the international community.

Another organization that the INMM has had a long and prosperous relationship with is the European Safeguards Research and Development Association (ESARDA), which is also celebrating its 50th anniversary in 2019.[4] INMM and ESARDA signed an MOU in 2011 for expanded cooperation and INMM members participate extensively in ESARDA annual meetings and Working Groups, as well as cooperation in the area of Education and Training.

ESARDA
European Safeguards Research & Development Association
1969~2019
50 years

And speaking of anniversaries that are significant to all of our organizations, this is the 50th anniversary of the Nuclear Nonproliferation Treaty (NPT).[5] The Institute will be celebrating that milestone as well during our 60th Anniversary Meeting.

A precursor of how intertwined that international treaty is with the INMM history, and how complicated the international political environment is with respect to the tenets upheld by the treaty, became apparent this year in Baltimore, as a special Nonproliferation & Arms Control Panel was held Thursday morning entitled *"NPT at 50 – What Next?"*. That panel of experts[6] examined the historical milestones of the NPT and the engagement of the Institute, and speculated on the Treaty's future as the world continues to be faced with challenges from many different actors, and the NPT itself finds challenges from many fronts, including the U.N. movement to ban nuclear weapons completely (the Treaty on the Prohibition of Nuclear Weapons, also known as the "Ban Treaty")[7] which some believe discredits the NPT's goal of disarmament. We can expect to see more informational presentations on this subject at next year's Annual Meeting.

The INMM Historical Timeline

As we approach the 60th Annual Meeting, the Strategic Planning Committee, in collaboration with the Executive Committee (EC), the Technical Divisions, Past President, Larry Satkowiak, and others have been working on a graphical timeline depicting major events that have influenced, or been influenced by, the Institute over its first 60 years. That timeline will be presented to the membership at the 60th Annual Meeting. A sampling of some of the dramatic world events that the Institute and its membership have been engaged with from various perspectives, includes the following:

- The Limited Nuclear Test Ban Treaty
- The first tests of nuclear weapons by France and China in the 1960's, creating a path for them as Nuclear Weapons States (NWSs), along with the U.S., the U.K. and Russia in the NPT.
- The NPT and the various protocols associated with the work of the IAEA.
- The first tests of nuclear weapons by India in 1974, and then India and Pakistan in 1998.
- The removal of nuclear weapons from three nation-states after the demise of the Soviet Union.
- The Nunn-Lugar Cooperative Threat Reduction Program.
- The Lab-to-Lab program.
- The Comprehensive Test Ban Treaty.
- The Intermediate Range Nuclear Forces (INF) Treaty.
- The Three Mile Island, Chernobyl, and Fukishima nuclear plant incidents.
- Nuclear weapons tests by North Korea in the first decade of the new millennium.
- The Prague speech by President Obama in 2009.
- The Joint Comprehensive Plan of Action with Iran.
- The modernization of the nuclear deterrent by all five of the NWSs.

And of course, there are many, many more.

The Technical Divisions will be reaching out to membership for milestones to add to the Timeline during the next year so that we have an historical picture of the influence and engagement of the Institute over these past six decades.

What Lies Ahead for the Next 60 Years?

As described in the previous "Taking the Long View" column,[8] at the closing plenary of the 59th Annual Meeting in Baltimore this year, the membership was challenged to think about the future of the Institute through a series of seven questions[9] created by the EC as a component of our new Strategic Plan. Stimulated by an international panel of five experts,[10] attendees were able to register their perspectives on remote polling devices, and results were documented to compare and contrast the perspectives of the five experts to the weighted perspectives of the attendees. The EC is analyzing the results of this exercise to help craft priorities for the Institute over the next couple of years, including a focus on future themes for the Annual Meeting. Some of those challenges identified during the plenary session, and as world events continue to shape our future, include the following:

- Concern was expressed by the membership and the panelists during the closing plenary session about the cyber vulnerabilities of nuclear security systems and the challenges presented by the rapid evolution of Artificial Intelligence (AI) technologies. These concerns are fueled almost every day in our world, as cyber hacking events capture the headlines, and the rapid advancement and proliferation of AI applications capture our imagination. With the revision of the U.S. Nuclear Posture Review (NPR) this year opening the possibility of the American nuclear arsenal serving a deterrent not only against nuclear threats, but also against "non-nuclear aggression," including cyber threats, and the growing automation of offensive systems, the literature has introduced the "doomsday" scenario of combining cyber, AI and nuclear weapons.[11] It is interesting to note that during the "NPT at 50" panel discussion held at this past year's Annual Meeting, cybersecurity was described as the potential "third rail" for the NPT moving forward. As noted in our previous "Taking the Long View" column, the Institute has already taken proactive measures to engage cyber discussions in all of our Technical Divisions through the creation of an interim Cyber/Physical Security Integration Committee.
- The challenges of a new Cold War, or "Cold War 2.0",[12] as the five NWSs aggressively move to modernize, and in some cases, expand their nuclear stockpiles. Concomitant with these modernization programs is an increasingly hostile public rhetoric driven by new political realities.[13]
- Socio-economic and political turmoil within the NWS countries, as each faces the rise of a new generation of technology-enabled voters living within a connected environment unlike anything previously experienced. These include:
    - **United States**: Continued partisan divide in the United States as the current Administration disrupts the normalized approach to governance. The divide has given rise to an animosity that pervades every day

dialogue and the news cycle.

- **United Kingdom**: Continuing complex issues associated with the Brexit issue in the U.K. have contributed to a political divide as well. As covered in previous “Taking the Long View” articles, not only does this have the potential for broad socio-economic impact, but it also brings into question the future of the nation’s nuclear deterrent, which depends on Scotland for the basing of its nuclear submarines.
- **France:** Recent political turmoil has demonstrated a growing disconnect between the current government and the general populace. The nation is also struggling with the continuing role of nuclear power within its electric infrastructure, as many facilities reach their end of life.
- **Russia:** Russia continues to take a more nationalistic stance with reliance on their nuclear stockpile. The tensions with the West, and the United States continue to increase, amid economic sanctions; lack of resolution of the Crimea/Ukraine situation; continuing tensions in Syria, and threats by the United States to withdraw from the INF Treaty due to violations by Russia.
- **China:** China continues on its path of securing islands in the South China Seas, with a growing frequency of confrontations by U.S. forces in the region, as the nation moves to become the global superpower. Internal political struggles surface occasionally despite the restrictive press, indicating that the nation is not without its own internal socio-economic issues.
- Socio-economic turmoil in many other nation-states as the new connected environment dramatically portrays the growing disparity between the “haves” and “have-nots”. This was no more clearly demonstrated than by the international movement this past year in the U.N. to pass, and release for signature, the Ban Treaty.

Clearly the challenges that lie ahead for the next 60 years will be no less engaging than those of the previous 60, since the formation of the Institute. It is up to the new generation to tackle these issues and offer the technical, scientific, and policy expertise of the membership to the world to help resolve them amicably, and preserve a bright future for mankind.

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.

Endnotes

1. The INMM was officially founded on May 17, 1958. The following year, on May 26, 2019, the Institute held, in essence, its first Annual Meeting – an INMM-AEC “Joint Meeting”. For more information on the history of the INMM, please see: https://www.inmm.org/About/History.aspx .
2. See https://www.iaea.org/about/overview/history for more information on the formation of the IAEA.
3. See: https://www.iaea.org/about/policy/gc/gc60 for more details on this 60th IAEA General Conference.
4. See https://esarda.jrc.ec.europa.eu/ for more information on ESARDA and the announcement for its 41st Annual Meeting to be held at the Regina Palace Hotel in Italy, May 14-16, 2019.
5. For a comprehensive look at the history of the NPT see: https://www.armscontrol.org/act/2018-06/features/npt-50-historical-timeline; https://www.armscontrol.org/factsheets/Timeline-of-the-Treaty-on-the-Non-Proliferation-of-Nuclear-Weapons-NPT; and https://armscontrol.org/act/2018-06/features/npt-50-staple-global-nuclear-order
6. The extraordinary session included panelists Laura Rockwood, Vienna Center for Disarmament and Nonproliferation; Susan Koch, National Institute for Public Policy; Joan Rohlfing, Nuclear Threat Initiative; and William Tobey, *Belfer Center for Science and International Affairs*.

7. See https://www.un.org/disarmament/wmd/nuclear/tpnw/ for complete information on this international effort.
8. See JNMM Vol. 46, No. 4, *"New Challenges for the Institute"*
9. Seven questions were provided to the panelists prior to the Closing Plenary with several multiple choice answers, including "other". After asking the attendees for their input, the panelists and the attendees were queried for more details. The questions posed were: 1) What is the current top global challenge/risk/threat with respect to nuclear proliferation?; 2) What is the current top global challenge/risk/threat with respect to nuclear security?; 3) Which risk set concerns you more?; 4) What are the greatest cyber threats related to nuclear materials management?; 5) What are the top 3 areas the INMM should focus on?; 6) Which technology has the best chance to become a "game changer" (plus or minus), for the INMM?; and 7) Where should the INMM increase its attention?
10. Panelists included Dr. Jacques Baute, Director, Division of Information Management, Department of Safeguards, IAEA; Dr. Bassam Abdullah Ayed Khuwalleh, Assistant Professor, Nuclear Engineering Program, University of Sharja; Mitsuo Koizumi, Manager of Technology Development Promotion Office of Integrated Support Center for Nuclear Nonproliferation and Nuclear Security of the Japan Energy Atomic Agency; Sonia Fernandes Moreno, Planning and Evaluation Officer, Brazilian-Argentine Agency for Accounting and Control of Nuclear Materials; and Julie Oddou, Head of the Committee Technique Euratom, Atomic Energy Commission (CEAR).
11. See: *"Pairing AI and nukes will lead to our autonomous Doomsday",* https://www.defensenews.com/opinion/commentary/2018/11/13/pairing-ai-and-nukes-will-lead-to-our-autonomous-doomsday/
12. See https://www.wilsoncenter.org/event/us-china-2018-year-review-new-cold-war
13. See "Putin hails U.S. withdrawal from Syria, warns nuclear war could destroy the planet" https://globalnews.ca/news/4780320/putin-russia-nuclear-war-syria/

Calendar

July 14-18, 2019
INMM 60th Annual Meeting
JW Marriott Desert Springs
Palm Desert, California, USA

August 4-9, 2019
PATRAM 2019
New Orleans Marriott
New Orleans, Louisiana USA

October 7-10, 2019
INMM-ESARDA-INMM Meeting
Tokyo International Exchange
Center Plaza HEISEI
Tokyo, Japan

For more information, visit the INMM Events Page.

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60th ANNUAL MEETING

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