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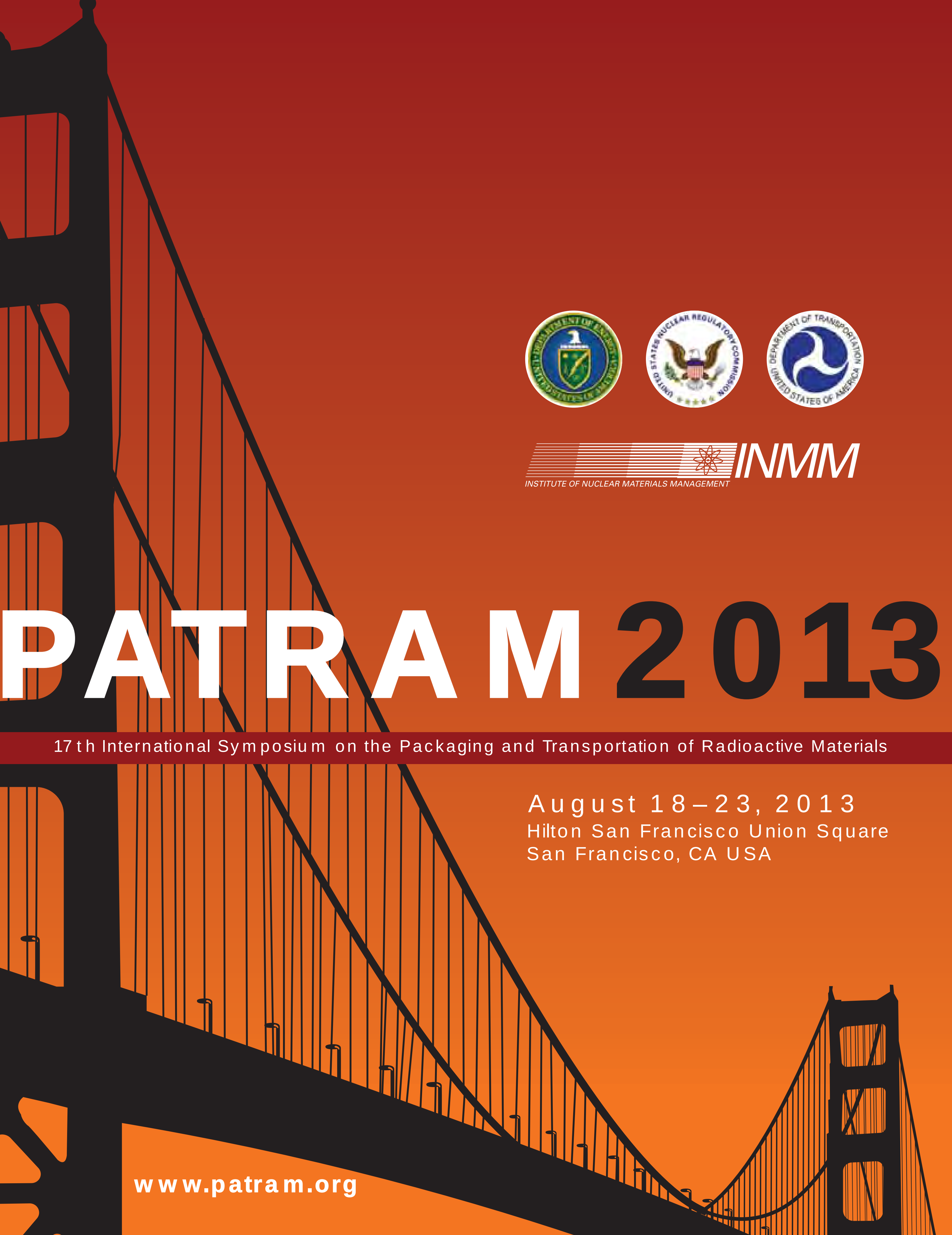

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Advertising Contact
Patricia Sullivan
INMM, 111 Deer Lake Road, Suite 100
Deerfield, IL 60015 U.S.A.
Phone: +1-847-480-9573;
Fax: +1-847-480-9282
E-mail: psullivan@inmm.org

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JNMM Journal of Nuclear Materials Management

Topical Papers

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Facing the Challenges

By Ken Sorenson
INMM President

Greetings! In my first column in the *JNMM*, I discussed transitions, challenges, and outlook. Given that we are in such a fluid time right now and that I also said to, "Stay tuned…," I would like to stay with this format and catch everyone up on where we are right now.

Transitions

Two committee chairs have submitted their letters of resignations to the INMM Executive Committee. The first, John Matter, is resigning from the Chapter Relations Committee. John has held many important positions at the INMM throughout his distinguished career, including president, 2003-2004. The Chapter Relations Committee was established in 2007, and John has been the chair from its inception. In this role, John has overseen the particular strong growth in our student chapters, as well as additional chapters outside of the United States. In all, we have twenty-eight chapters spanning the globe. Thank you, John, for your stewardship of this important activity.

Second, Rick Rawl has resigned from his position of chair of the ASC N14 Technical Committee, which is responsible for the preparation of standards for the packaging and transportation of fissile and radioactive materials, as well as non-nuclear hazardous materials including waste and mixed materials. The INMM is the sponsoring organization and secretariat for this ANSI committee. Rick has served many years in this position for the INMM. Thank you, Rick, for your leadership on this committee. The Executive Committee is taking steps to fill these positions as soon as possible.

Finally, resulting from the INMM elections, Larry Satkowiak was elected vice president of the Institute and has had to step down as chair of the Nonproliferation and Arms Control Technical Division. Joyce Connery has been selected to replace Larry as the chair. Joyce works for DOE/NNSA and comes with a wealth of technical and leadership experience to bring to bear for this important technical division. Welcome, Joyce.

Challenges

We have a major challenge facing the INMM this year and for the foreseeable future. The recent U.S. Office of Management and Budget (OMB) guidance that limits U.S. federal employee and federal contractor attendance at conferences and workshops became a major issue for our annual meeting this past year. We lost approximately 200 potential U.S. registrants due to this guidance.

Why is this important to our non-U.S. membership? The INMM Annual Meeting and associated workshops are the lifeblood of the Institute. At these meetings, the mission of the INMM is executed through the important policy, programmatic, and technical discussions that occur. The global nature of the INMM mission is a compelling argument for the importance of the INMM meetings.

As the U.S. Department of Energy is a large supporter of the work that is conducted in the United States and abroad, limiting participation of U.S. DOE and DOE-sponsored participants constrains this collaborative exchange. In addition to the mission aspects, the meetings that the INMM sponsors generate revenue that sustains our operations through an annual budget cycle. While the 53rd Annual Meeting last July was successful, the revenues generated were far below what was budgeted. As a result, we are planning to restrict certain activities in the FY13. In particular, you will see fewer INMM-sponsored workshops this year.

What are we doing about this? The INMM leadership is being proactive on a number of fronts. First, we have submitted a waiver letter to DOE detailing the benefits that the INMM annual meeting has for the DOE. This letter, once signed by the Secretary of Energy, will allow DOE and DOE-sponsored attendance at the 54th Annual Meeting at a level that we had in the 2010 and 2011 annual meetings. Second, we are drafting letters for congressional delegations detailing the impact of the OMB restrictions on their particular state's economy and asking for attention to this matter. Third, we are drafting letters that will go to other non-government organizations in similar situations to contact their congressional representatives. Fourth, we are soliciting INMM committee chairs to identify professionals in this field who can write testimonials to DOE leadership to explain the importance of INMM to the DOE mission. And, finally, INMM officers are planning to meet personally with select DOE management to explain the INMM mission and its relevance to important DOE programs. We hope that the direct result that you will see from these efforts is a very well attended 54th Annual Meeting!

Outlook

Given the transitions and challenges that the Institute faces, I am extremely optimistic about INMM's future. Global issues regarding the management of nuclear materials are real and need the membership expertise and institute backing that the INMM provides. Our global reach through all of our chapters, and our partnerships with important sister technical organizations such as the World Institute for Nuclear Security (WINS), ESARDA, and the Nuclear Infrastructure Council (NIC), provide the leverage to make INMM a leader in the field.

I look forward to working with all of you on issues directly affecting the Institute as well as on broader nuclear materials management concerns. Feel free to contact me directly at any time.

INMM Loses a Stalwart Supporter

By Dennis Mangan
INMM Technical Editor

In this issue, on Page 41, is an *Obituary* for Edway (Ed) Johnson.[1] This dear friend and staunch INMM supporter passed away on November 28, just two weeks shy of his 85th birthday. As you read about Ed's efforts within our organization you will be impressed. There was one interesting effort by Ed of which most people were not aware, and it's not in the *In Memoriam*. Back in the mid-1970s, Ed became leader of the INMM Transportation and Spent Fuel Working Group. At that time there were a few of other working groups, if I recall correctly, one in physical protection, one in material control and accounting, and one in international safeguards. At the 1982 Annual Meeting, the INMM officers and a few of the INMM Fellows got together for a discussion. Ed was one of those Fellows. During the course of the conversation, Ed suggested that the officers give consideration to reorganizing the Institute in a more formal and easily recognizable structure that addressed the needs of responsible nuclear materials management. His objection was that people outside INMM had no idea what was accomplished in these so-called working groups, as well as what other areas of interest existed. After considerable discussion and reflection, the idea of having structured technical divisions with mission statements and with chairs and committees involved in running these new divisions evolved. Five such technical divisions were identified: Waste Management, Materials Control and Accountancy, Physical Protection, International Safeguards, and Transportation and Packaging. About a year later, the Nonproliferation and Arms Control Technical Division was added. As many people realize, having these structured technical divisions were instrumental in the growth of our Institute. Ed was the leader involved in their formulation.

I appreciate the format that our new President, Ken Sorensen, has adopted for his President's Message: *Transitions, Challenges, and Outlook*. It captures three broad areas that interest our readers.

In this issue, we have three technical papers:

- *Simulation and Experimental Validation of Electromagnetic Signatures for Monitoring of Nuclear Material Storage Containers* by A. Mark Jones, Kyle Bunch, and Pamela Aker from Pacific Northwest National Laboratory (PNNL), Richland, Washington USA. This paper discusses an interesting concept.
- *The IAEA Workshop on Requirements and Potential Technologies for Replacement of ^{3}He Detectors in IAEA Safeguards Applications* by: Mark Pickrell and Anthony Lavietes from the International Atomic Enery Agency (IAEA), Vienna, Austria; Victor Gavron, Daniela Henzlova, and Howard Menlove, from Los Alamos National Laboratory, Los Alamos, New Mexico, USA; Malcolm Joyce from Lancaster University, Lancaster, UK; and Richard Kouzes, PNNL. This paper addresses a significant future concern of the IAEA.
- *Further Intrusion or Different Political Priorities? What Are the Main Reasons Behind Countries' Non-Signature of the IAEA Additional Protocol?* by Sara Kutchesfahani from Los Alamos National Laboratory, Los Alamos, New Mexico, USA. This paper is an interesting study regarding the application (or lack thereof) of the Additional Protocol.

Industry News Editor, Jack Jekowski, chair of the Institute's Strategic Planning Committee, discusses the strengths of our Institute. It's a very interesting article.

Finally, Mark Maiello, our book review editor, provides a review of a book titled *Nuclear Politics and the Non-Aligned Movement* by William Potter and Gaukhar Mukhatzhanova. I have to admit that I didn't know what was meant by the Non-Aligned Movement until I read this review.

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

JNMM *Technical Editor Dennis L. Mangan may be reached at dennismangan@comcast.net*

Note

1. This *In Memoriam* was prepared by Managing Editor Patricia Sullivan with the help of Charlie Vaughn, Yvonne Farris, John Lemming, and Scott Vance.

Simulation and Experimental Validation of Electromagnetic Signatures for Monitoring of Nuclear Material Storage Containers

A. Mark Jones, Kyle J. Bunch, and Pamela M. Aker
Pacific Northwest National Laboratory, Richland, Washington USA

Abstract

Research at the Pacific Northwest National Laboratory (PNNL) demonstrated that the low frequency electromagnetic (EM) response of a sealed metallic container interrogated with an encircling coil is a strong function of its contents and can be used to form a distinct signature confirming the presence of specific components without revealing hidden geometry or classified design information. Finite element simulations further investigated this response for a variety of configurations of an encircling coil and a typical nuclear material storage container. Excellent agreement was obtained between simulated and measured impedance signatures for electrically conducting spheres placed inside an AT-400R nuclear material container. Simulations determined the effects of excitation frequency and of the geometry of the encircling coil, nuclear material container, and internal contents. It is possible to use electromagnetic models to evaluate the application of the EM signature technique to proposed versions of nuclear weapons containers which can accommodate restrictions imposed by international arms control and treaty verification legislation.

Introduction

The U.S. government is interested in developing technologies that can be used to construct attribute measurement systems with information barriers (AMS/IB) for arms control and treaty verification purposes. There is a wide range of technologies that can be included in an AMS/IB system. However, the optimal choice of specific technologies included in an AMS/IB system will be determined by factors such as system cost, measurement effectiveness, measurement time, measurement flexibility, system robustness, ability to protect classified information, confidence in the result, and time to implement and certify the technology for use in monitoring applications.

The electromagnetic (EM) coil impedance technique is one low-intrusion, non-nuclear measurement technology that could be used in a simplified AMS/IB system. It can be used to provide a history of the properties of an individual item using an inexpensive, rapidly obtained simple measurement. When combined with other easily obtained attributes, the technique can be used as a measurement baseline on a single item, or a class of items, which is periodically recorded and the changes in measurements used to identify and address safety or tampering concerns.

The EM technique depends on the eddy currents induced within a conducting material. This response field changes the complex impedance of the coil inducing the response currents. Eddy current techniques have been used for many years as a non-destructive method to characterize both material properties[1] and geometric variations.[2-5] High frequency eddy-current systems with direct magnetic-field imaging have been used for surface crack inspection.[6] The significant feature of the technique described in this paper is the use of low frequency magnetic fields that can penetrate encasing containers and interact with stored materials. Using the impedance response of a large coil yields a bulk measurement that inherently hides detailed target geometry while still providing enough information for a useful signature.

It is possible to rapidly measure the complex impedance of an external coil surrounding a closed canister containing a sample object.[7] This technique provides different mutual inductance values when different materials are placed within a coil excited with low-frequency current. A simple physics analogy of this measurement is the change in inductance of a tunable radio coil when a core of magnetic material is placed inside the coil.

The coil is constructed by winding copper wire around a hollow cylinder. An analyzer can be used to measure the coil's electrical impedance, which is determined primarily by the electromagnetic properties, extent, orientation, and distribution of materials inside the coil. The electrical impedance of the coil is a complex quantity signified by the coil's response to an applied voltage according to Ohm's Law for AC circuits. The two frequency-dependent impedance components are resistance and reactance. Resistance is the real component, and reactance is the imaginary component derived from electromagnetic theory and includes the capacitance and inductance. Coil impedance is typically written as $Z = R + iX$, where Z is the complex impedance, R is resistance and X is the combined inductive and capacitive reactance (all quantities are in Ohms).

Figure 1 is a schematic of an electrical impedance arrangement in which a sinusoidal voltage applied to the primary circuit

Figure 1. Equivalent circuit for coil-based container inspection technique

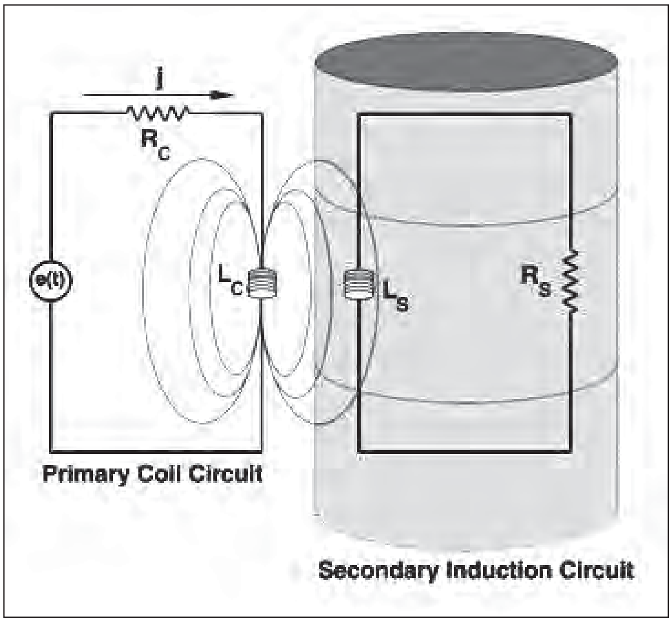
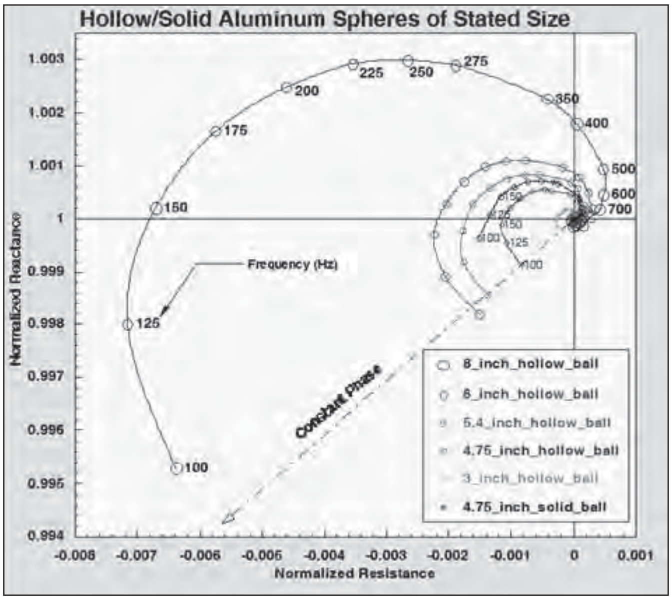


Figure 2. Normalized coil impedance measured for aluminum spheres inside AL-R8 container



coil generates an AC magnetic field. The magnetic field penetrates the container and induces eddy currents in the internal objects according to Faraday's Law of Induction. The induced current flows inside and through the container and generates a secondary magnetic field according to Ampere's Circuit Law. The total magnetic field influencing the coil is thus the combination of the primary and secondary magnetic fields. This magnetic field determines the coil impedance, which can be measured by connecting an impedance analyzer to the coil via a coaxial cable. Hence the measured coil impedance serves as a signature of the electromagnetic properties of all objects inside the coil.

The most significant parameters that affect the magnetic field coupling are the dimensions and electrical properties of the container. However, a much smaller but more interesting effect of the EM field coupling phenomena is the change in coil impedance that results when electrically conducting objects are placed inside the container. To separate and obtain the coil impedance change resulting from the contribution of the contents, it is necessary to have the coil response of the empty as well as the loaded container. This is obtained by measurement of the container empty and with the items of interest. The apparent EM coil impedance can be calculated from both the empty and loaded container coil impedance measurements using the equation[8]

$$Z_n = \frac{Z - R_o}{X_o} = \frac{R - R_o}{X_o} + i\frac{X}{X_o},$$

where $Z = R + iX$ is the complex coil impedance for the loaded container, $Z_o = R_o + iX_o$ for the empty container, and R_o and X_o represent the "empty container" resistance and reactance respectively. Z_n represents the apparent coil impedance of the objects inside the container normalized to the empty container. The plot in Figure 2 is an example of the apparent coil impedances for a series of spherical aluminum objects located within a carbon steel AL-R8 container. Note that the measurements have been made at several different frequencies.

The term *apparent coil impedance* is used here because the object of interest would not produce the same coil impedance if it were placed inside the coil without the storage container present or if it were placed inside a different storage container. The apparent coil impedance of an object inside a metal container depends upon the container it is stored in. The only means to completely remove all container effects from the measurement is to use a non-conductive container that is transparent to the excitation fields.

A series of experiments performed in the mid-nineties at Pacific Northwest National Laboratory (PNNL) for a set of aluminum spheres contained within a carbon steel AL-R8 nuclear material container demonstrated that the EM coil method is frequency dependent. In these experiments, a coil was excited with AC current in the range from 100 to 1500 Hz. As shown in Figure 2, only frequencies below 800 Hz were capable of producing a measurable interaction with electrically conducting objects inside the container. As the frequency falls below 800 Hz, a noticeable change begins to emerge in the normalized impedance curves for different objects located inside the same container. However, this frequency is specific to the AL-R8 container and may not be applicable to other packages. The upper frequency value is a strong function of the container design and can be significantly different for containers made from materials having different magnetic permeability and electrical conductivity values. Container wall thickness also affects the upper frequency value.

Since the successful application of this inspection method strongly depends upon the container design, a study was performed to investigate the impact of container dimensions and material properties on the electromagnetic response of the coil. Since experimental characterization of a complete set of these parameters is unrealistic, we have used an electromagnetic simulation tool that can model coil measurements on any system. The following sections describe the software package and computational procedures that we used to model the coil responses of a variety of different metallic objects housed within an AT-400R nuclear material package. We outline what type of information is needed to perform the simulations and compare the theoretical results with recent experimental measurements. The excellent agreement demonstrates that our modeling procedures are very robust. We then discuss the different outcomes that result when the electromagnetic properties, geometries, and dimensions of both the container and contents are varied. We also show how simulations can be used to optimize the frequency at which experiments should be conducted.

Simulation Methodology

The computation of an eddy current signal involves a solution of Maxwell's equations with appropriate boundary conditions at the material interfaces. The materials involved are characterized by their electrical conductivity, dielectric constant, and magnetic permeability. Although the basic approach to a given eddy current problem may be straightforward, it is likely to be difficult to obtain a solution in a closed mathematical form. Many analytical solutions to eddy current problems have been derived, but mathematical difficulties ultimately limit such solutions to cases involving relatively simple geometry.

With the availability of computers, analytical approaches have largely been abandoned in favor of numerical methods that convert the problem into one involving the solution of a large set of algebraic equations. Implementations of this general approach include the finite element method, the boundary element method, and a hybrid combination of these two methods. In each of these numerical methods, the governing differential equations are converted into a set of coupled linear equations by dividing the solution space into small volume or surface elements. Commercial software packages now make it possible to accurately solve complex eddy current problems that involve multiple conductors and complex geometric configurations.

The Ansoft Maxwell simulation software package[9] was used to model the coil and container configurations in this study. The Maxwell software is based on the finite element method and includes a suite of static, frequency-domain, and transient electromagnetic field solvers. Maxwell can be used to model electromagnetic and electromechanical devices such as motors, actuators, transformers, and coils. Output quantities available from the solution include electromagnetic field visualizations and numerical parameters such as force, losses, and impedance. The eddy current solver was used for this study in order to study the frequency-dependent effects of the excitation current on the coil impedance.

The Maxwell software uses an automated adaptive meshing algorithm that iteratively increases the mesh density until the specified solution accuracy has been reached. This algorithm eliminates the need for the user to manually create a mesh for each geometric model. The Maxwell software also includes an advanced meshing feature which can re-use the final mesh obtained from one model in another model. For this study, identical finite element meshes were used for the empty and loaded containers in order to prevent any small mesh differences from influencing the results.

Although the software includes 3-D and 2-D field solvers, it is good practice to use 2-D modeling, when appropriate, in order to minimize solution time and resource usage. The same output quantities are available from the 2-D and 3-D field solvers. The 2-D models can be based on Cartesian (XY) or rotational (RZ) symmetry. All cases shown here were modeled using the 2-D axisymmetric solver due to the existence of rotational symmetry.

Validation of Simulation Methodology

Since one objective was to confirm that the coil simulations accurately predict experimental measurements, the physical and material parameters of the coil, container, and objects within the container need to be known with a high degree of confidence. The coil used for the laboratory measurements was the dual position encircling air-core coil shown in Figure 3. The lower and upper coils are identical. Only the lower coil was used in these experiments. This coil was originally constructed in the mid-nineties and the exact fabrication details are unknown. The DC resistance and inductance values were measured with an impedance analyzer and RLC meter to be 28 Ohms and 132 mH. These values were used to determine that the coil consists of 450 turns of 20 AWG copper wire wrapped around a phenolic paper laminated tube. The coil diameter was measured as 22.25 inches and coil height was measured as 9.5 inches. A stranded conductor current source excitation on the coil cross-section was used in the Maxwell software simulations.

The AT-400R package is constructed from type 304L stainless steel with a high-density insulating foam liner and a welded inner containment vessel. A cross-section through the container is shown in Figure 4. The wall of the inner containment vessel is 0.250 inches thick with a 13.5-inch inner diameter. The inner containment vessel sits between two foam-filled inserts inside the outer container. The outer container dimensions are approximately 20 inches in diameter by 28 inches high. The containment vessel is fabricated from type 304L stainless steel. Fabrication drawings were obtained from Sandia National Laboratories in order to create the geometrical models.

Figure 3. Encircling coil used in measurements and simulations of AT-400R container

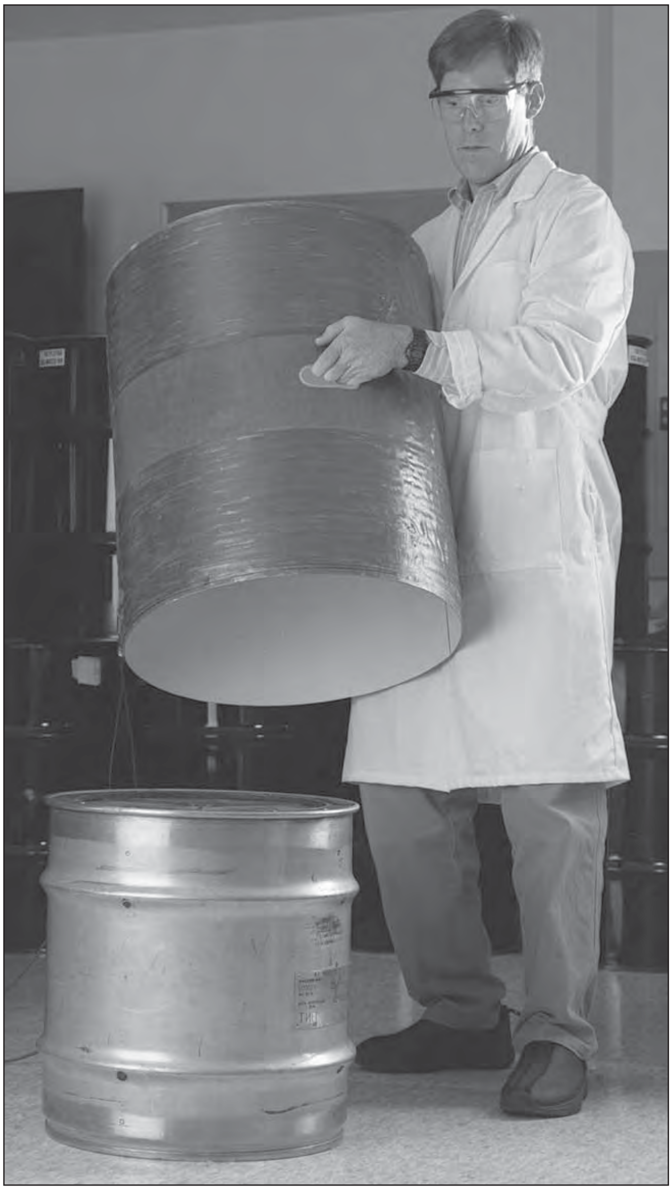


Figure 4. Cross-section showing construction of AT-400R nuclear material storage container

Figure 5. Conducting spheres placed inside AT-400R container and model of the experimental setup

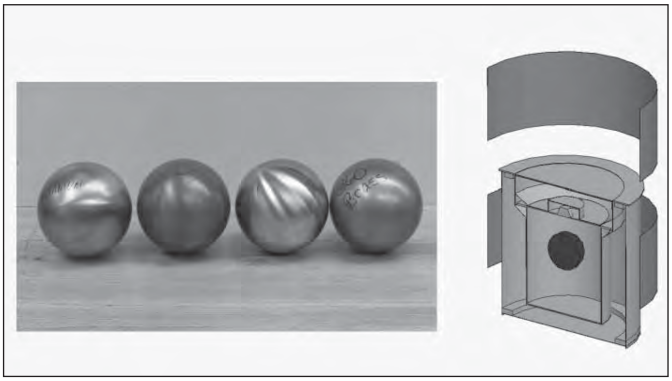


Table I. Measured electrical resistivity and equivalent conductivity values for conducting spheres

Sphere Type	Electrical Resistivity (μW-cm)	Electrical Conductivity (S/m)
Copper	1.8	5.56E7
Brass	8.5	1.18E7
Stainless Steel 304	68	1.47E6
Titanium	160	6.25E5

Coil impedance measurements were performed for each of four different 4.75-inch diameter solid conducting spheres located in the center of the closed AT-400R container. A measurement was also performed for the empty container in order to normalize the coil impedance values. The conducting spheres and a model of the experimental arrangement are shown in Figure 5. Each sphere was supported inside the container on a tubular Plexiglas pedestal. The excitation frequency was swept between 100 and 3,000 Hz in 10 Hz increments. The coil impedance was recorded with sixteen-point averaging and a 5 Hz bandwidth. The spheres were made of brass, copper, titanium, and Type 304 stainless steel. A four-point probe was used to measure the electrical resistivity and equivalent conductivity values listed in Table I. All of the spheres are non-magnetic and thus have a relative permeability of unity.

Figure 6. Measured and predicted normalized coil impedance for conducting spheres inside AT-400R container

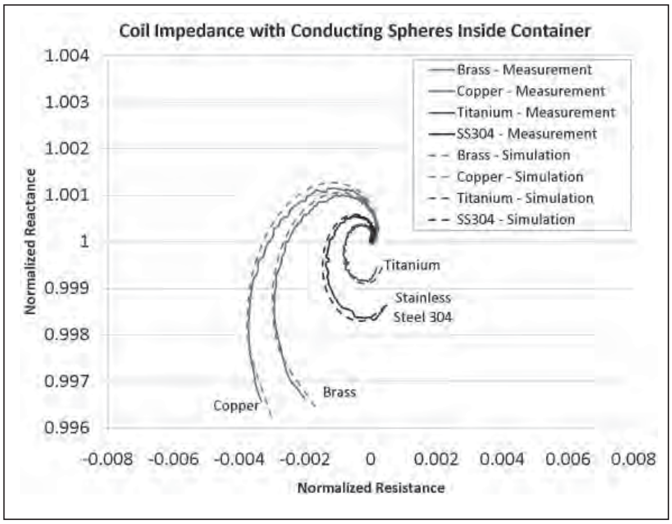
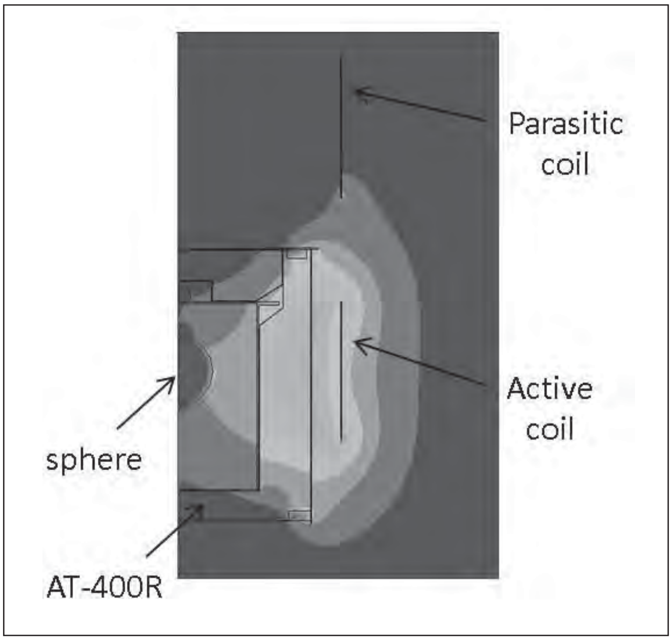


Figure 7. Predicted magnetic field distribution for 500 Hz coil excitation



The Ansoft Maxwell 2-D eddy current solver was used to calculate the AC resistance and inductance of the coil with the container loaded with each sphere. A simulation was also performed for the empty container in order to normalize the predicted coil impedance. As shown in Figure 5, each conducting sphere was centered inside the cylindrically symmetric AT-400R container, which was positioned in the center of the encircling coil. The coil was modeled as copper, the container was modeled as Type 304L stainless steel, and the upper parasitic coil was also included in the model. Each sphere was assigned the appropriate conductivity as shown in Table I.

Simulations were performed with the excitation frequency varied between 100 and 3,000 Hz in 50-Hz increments. Since the stranded conductor current source models the coil as a rectangular cross-section instead of including each turn, it does not provide the total coil resistance, which includes the AC as well as DC resistance. However, this is not an issue since the coil signature is based on relative impedance changes (normalized to the empty container) and the DC resistance would cancel out during the normalization procedure. The DC resistance could also be calculated from the physical parameters of the wire and added to the AC resistance predicted from the simulations. Simulations of the empty coil at DC yielded an inductance of 129 mH, which is in excellent agreement with the 132 mH measured value.

Figure 6 shows the normalized coil impedance values for the measurements and simulations for the AT-400R nuclear material storage container loaded with each of the conducting spheres. There is excellent agreement between the measured and simulated complex impedance values versus frequency. Any small differences can be attributed to uncertainties regarding the exact details of the encircling coil and AT-400R container construction. Figure 7

Figure 8. Effects of excitation frequency on magnetic field distribution for model of brass sphere inside AT-400R container

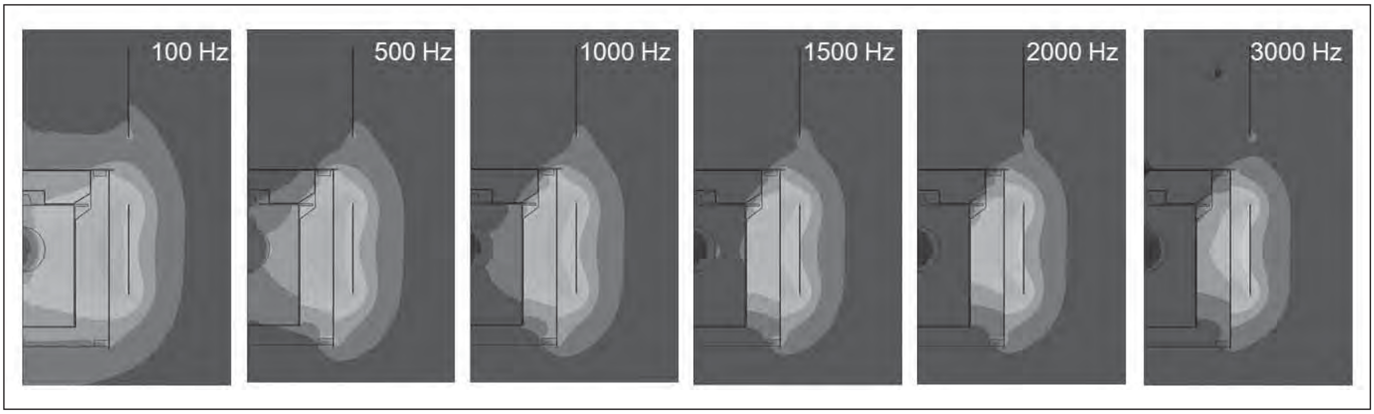


Figure 9. Predicted magnetic field distribution at 500 Hz for AT-400R container and brass sphere with different coils

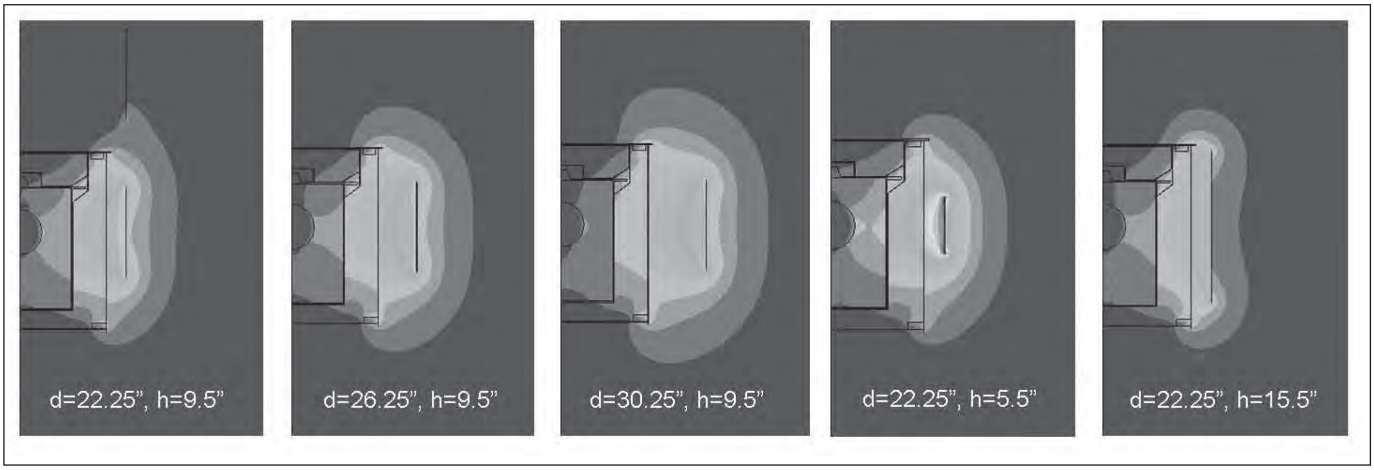
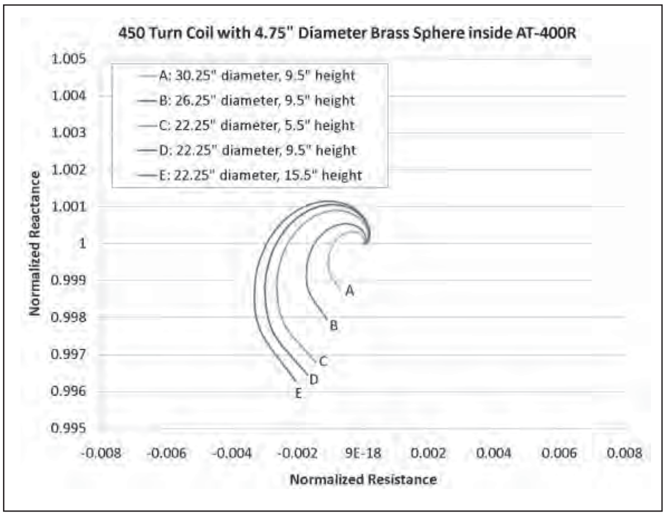


Figure 10. Effect of coil geometry on normalized coil impedance for models of AT-400R container and brass sphere



shows the geometry used in the 2-D simulations and a gray-scale plot of the magnetic field distribution when the coil is excited with a 500 Hz current. Lighter shading indicates stronger magnetic fields and darker shading indicates weaker magnetic fields. It can be seen that at this frequency the magnetic field penetrates the outer and inner container walls and interacts with the sphere.

The excellent agreement between the simulation and experimental results provides validation that the Maxwell eddy current solver can be used as a predictive tool for developing and optimizing new EM coil sensor systems. In the next section we show how simulations can be used to optimize the coil excitation frequency, and how variations in container and content physical dimensions and electromagnetic properties impact coil impedance measurements. The results of these investigations demonstrate how simulation tools can be used to accelerate the sensor and container design process and thus reduce system development cost.

Performance Investigation via Simulation Studies

Excitation Frequency

Eddy currents are created in conducting objects located inside a sealed container only when the external oscillating magnetic field can penetrate the container walls. Since the coil impedance signature method is based upon the magnetic fields set up by these eddy currents, it is important to understand the field interactions that occur within a given container. It is known that the eddy current penetration depth, d, is given by $d = 1/\sqrt{(\pi f \mu s)}$,[10] where f is the frequency, μ is the magnetic permeability and s is the electrical conductivity. This skin depth equation provides the distance at which the exponentially decaying magnetic fields have been reduced to 37 percent of their initial value at the surface. Typically one may presume that complete shielding has occurred for conductor thicknesses greater than three to five penetration depths. However, detailed EM simulations are preferred over simple calculations when multiple layers of conductors with potentially different properties are involved in the field interactions.

We used the Maxwell 2-D post-processor to visualize the calculated magnetic field distributions for the cases shown in Figure 6 in order to study the field penetration into the container. Figure 8 shows the frequency-dependent magnetic field distributions from 100 Hz to 3,000 Hz with a 4.75 inch diameter brass sphere located inside the containment vessel. The results show that lower coil excitation frequencies provide greater magnetic field penetration, as expected from the general penetration depth equation. Careful selection of this frequency range is required in order to successfully apply the coil signature method to a nuclear material storage container.

For the AT-400R container, the plots show that the magnetic fields are confined to regions outside the inner containment vessel for frequencies above approximately 1,500 Hz. Using frequencies above this range will not add new information about the internal contents of the AT-400R container to the impedance

Figure 11. Predicted magnetic field distribution at 500 Hz for brass spheres of different sizes inside AT-400R container

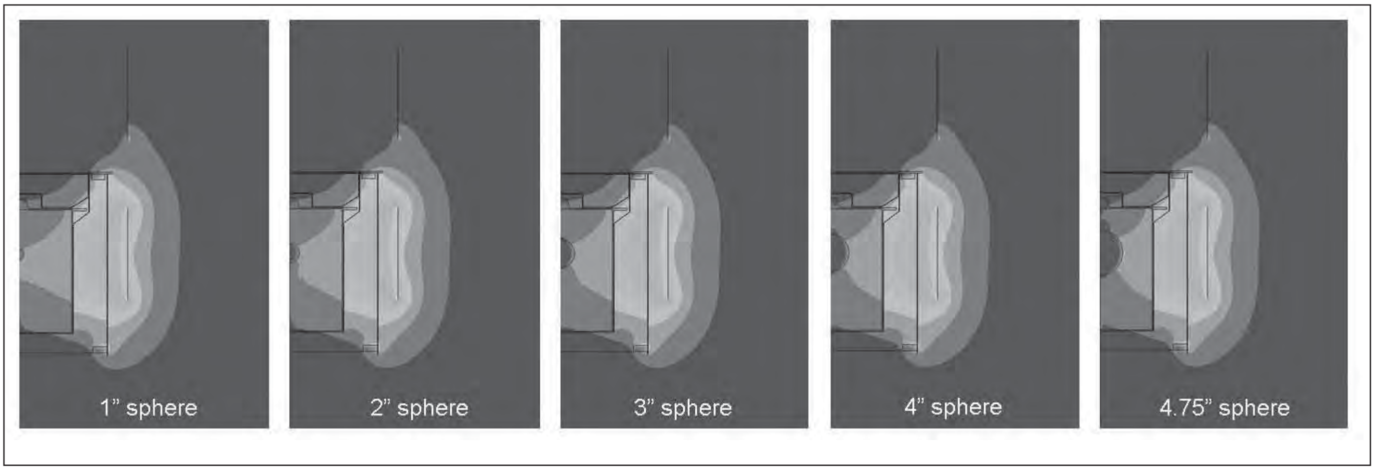
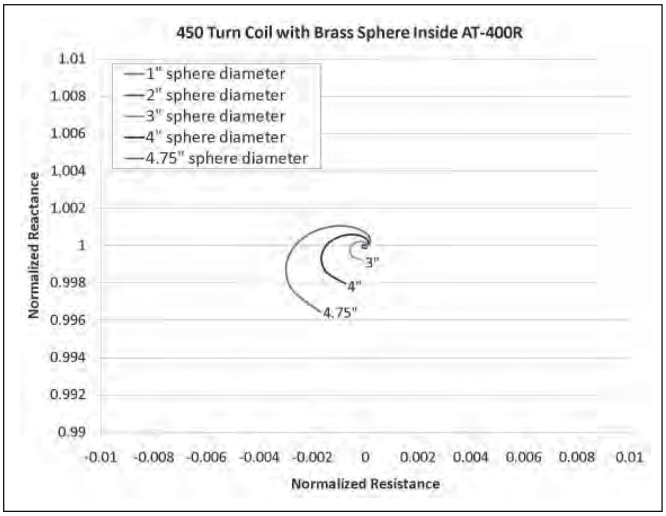


Figure 12. Effect of sphere diameter on normalized coil impedance for models of brass sphere inside AT-400R container



signature. Similar field behavior was observed for the other metal sphere samples. In addition to 2-D field visualizations, 1-D line plots can be generated along any desired direction to investigate field values in detail. It is evident that simulations allow close inspection of the magnetic field distribution for a configuration of interest and thus enable a better understanding of the physics underlying this sensing technique.

Coil Geometry

The coil geometry also plays an important role in the proper design of a system used to collect impedance signatures. In order to evaluate some of these effects, we performed a parametric study of coil diameter and height. The geometry consisted of an encircling coil and an AT-400R container with a 4.75-inch diameter brass sphere located inside the containment vessel. The baseline coil had a diameter *d* of 22.25 inches and a height *h* of 9.5 inches. The coil diameter was first increased by four and eight inches, which doubled and tripled the separation between the coil and the outer wall of the container. The coil height was held constant at the baseline value for these models. The coil height was then modified to 5.5 and 15.5 inches with the diameter held constant at the baseline value. All simulations were performed for excitation frequencies between 100 and 3,000 Hz in 50 Hz increments, and the magnetic field distributions and normalized impedance changes were extracted using the post-processor.

The predicted magnetic field distributions for the different sized coils using a 500 Hz excitation frequency are shown in Figure 9. The predicted apparent coil impedances normalized to the empty container are shown in Figure 10. These results show that increasing the coil diameter reduces the magnetic field penetration depth and that a coil with a larger height produces a larger signature. However, using a coil with a height larger than the container may introduce uncertainties in the measurement due to the potential for higher interference from external objects. As shown in Figure 10, increasing the coil diameter significantly decreases the detection sensitivity. Decreasing the coil height also causes a reduction in sensitivity, but the effect is not as large as is seen with the increase in coil diameter. By using these types of simulations, the physical dimensions of a coil can be optimized for a particular container.

Object Size and Geometry

The baseline model of the coil and AT-400R was used to study how the size of the object housed inside the container impacts detection sensitivity. As an example, a solid brass sphere was centered inside the closed container and the sphere diameter was changed to 1, 2, 3, 4, and 4.75 inches. The simulations were performed for frequencies from 100 Hz to 3,000 Hz in 50 Hz increments. The magnetic field distributions for a coil excitation frequency of 500 Hz are shown in Figure 11. There is little variation in the field intensities in the region outside the inner con-

Figure 13. Predicted magnetic field distribution at 500 Hz for containers with different wall thicknesses

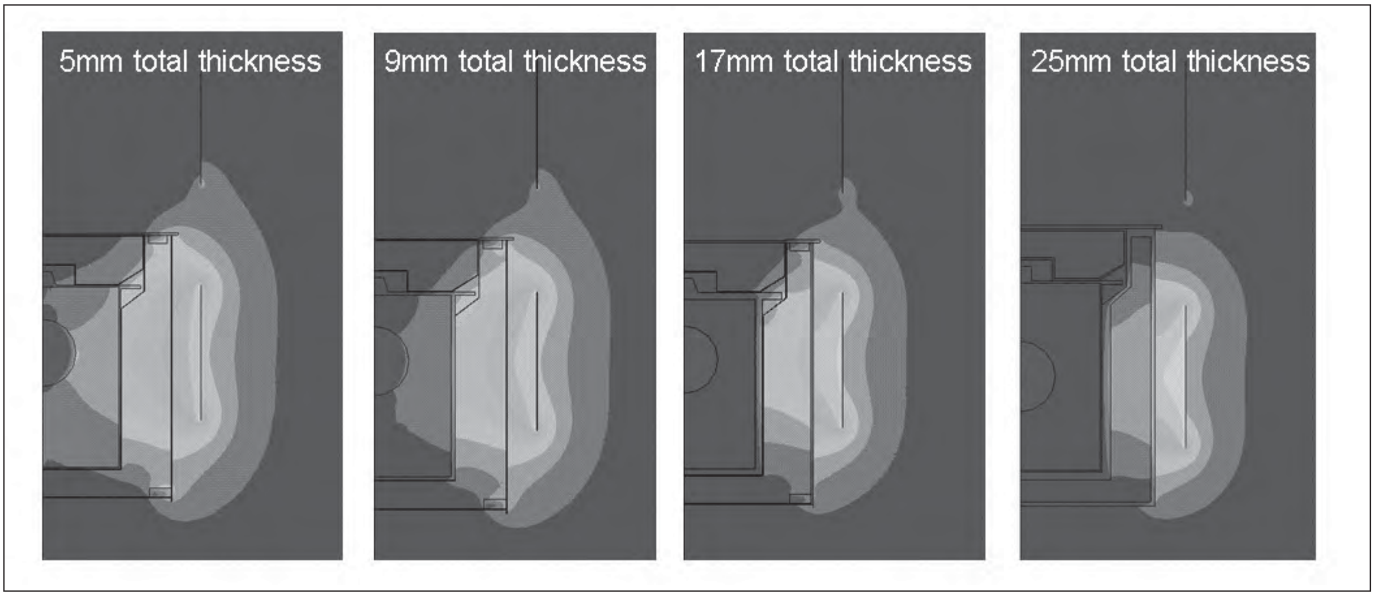
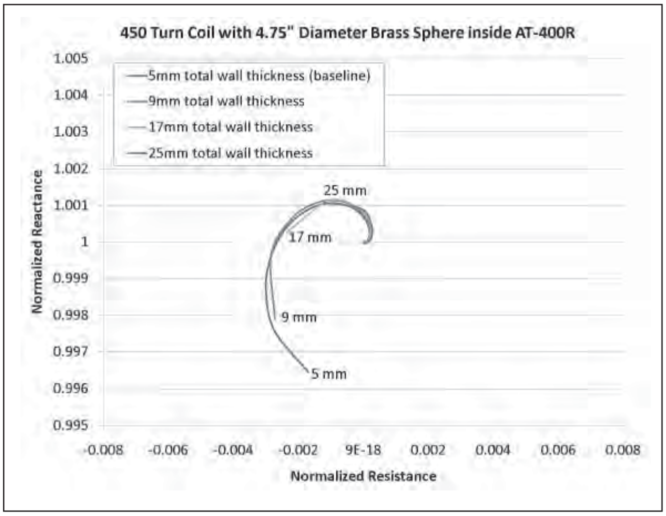


Figure 14. Effect of container wall thickness on normalized coil impedance for models of brass sphere inside container



tainment vessel, and the only variation in field intensities inside the inner containment vessel occur at the surface of the sphere.

Figure 12 shows the apparent impedances normalized to the empty container as a function of sphere diameter. The one-inch- and two-inch diameter spheres produce normalized impedance changes less than 10^{-4} and would be difficult to detect. Hence the smallest detectable solid brass sphere for this example scenario is one with a three-inch diameter.

The eddy currents that give rise to the unique coil signature of a loaded container are a function of the shape of the objects inside the container. The magnitude of eddy currents produced by the interrogating field is dependent upon the conducting material present in the plane perpendicular to the interrogating magnetic field. Objects with a rectangular, oblong, or cylindrical shape will produce a signature that is different from objects having a spherical shape. 3-D simulations can be used to determine the coil impedance response for arbitrarily shaped objects inside a container.

Container Properties

The container physical and electromagnetic properties are perhaps the most influential parameters for the coil impedance signature technique. The container presents the highest barrier between the excitation fields and the objects to be characterized. We performed a study of how two container properties, the wall thickness and magnetic permeability, impact the detection sensitivity. The baseline model of the coil and existing AT-400R container were used as the comparison data, and all simulations included a 4.75-inch diameter solid brass sphere inside the container. The excitation frequency was varied between 100 and 3,000 Hz in 50 Hz increments.

The AT-400R container has three type 304 stainless steel walls between the coil and the sphere. To characterize the impact that container wall thickness has on detection sensitivity, we varied the inner containment (IC) vessel wall thickness between 3 and 12 mm, the overpack inner (OI) wall thickness between 1 and 14 mm, and the overpack outer (OO) wall thickness between 1 and 8 mm. Figure 13 shows the predicted magnetic field distributions at 500 Hz for IC:OI:OO dimensions of 3:1:1, 6:1:2, 12:1:4 and 3:14:8 mm, which have total wall thicknesses of 5, 9, 17, and 25 mm, respectively. The results show that increasing the container wall thickness significantly reduces the magnetic field intensity in the inner containment vessel and at the surface of the brass sphere.

Figure 15. Predicted magnetic field distribution at 500 Hz for containers with different relative magnetic permeability

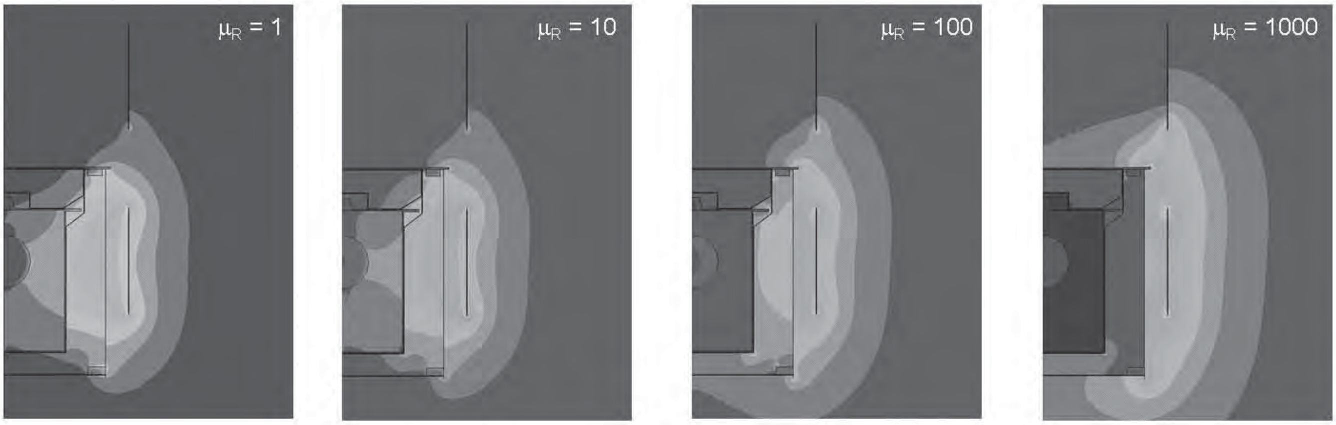


Figure 16. Effect of container magnetic permeability on normalized coil impedance for models of brass sphere inside container

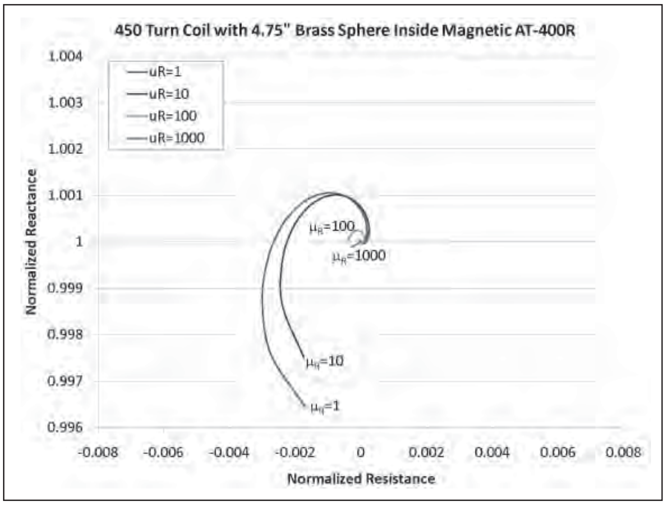


Figure 14 shows the apparent coil impedances for the models with the IC:OI:OO geometries described previously. Increasing the total wall thickness reduces the detection sensitivity at the low end of the frequency sweep. As the container wall thickness increases, the magnetic field penetration at a given frequency is reduced. Again we see the benefit of using simulations to evaluate the performance of the electromagnetic signature method for a proposed container geometry.

The next parameter that was explored was the container wall magnetic permeability. Depending upon the type of material used to construct the container, the relative permeability can vary from 1 to over 1,000. For example, the 300 series of stainless steels are non-magnetic while carbon steels are strongly magnetic. This series of simulations was performed using the same sphere and coil geometry described above and the baseline AT-400R container geometry. The container electrical conductivity was held constant while the relative magnetic permeability was varied between 1 and 1000. The excitation frequency was swept between 100 and 3,000 Hz in 50 Hz increments.

Figure 15 shows the predicted magnetic field distributions for the different magnetic permeability values for a coil excitation frequency of 500 Hz. The magnetic field intensity inside the container is quite strong for values of μ_R between 1 and 10, but becomes negligible when μ_R is increased to 100 or higher. Figure 16 shows the predicted apparent impedance for these cases for the entire frequency band. As expected from the magnetic field plots, the coil impedance drops off significantly for values of μ_R higher than 100. This indicates that containers constructed from carbon steels require the use of a lower frequency to form a signature of the contents and yield a smaller signature than the same container made from a non-magnetic stainless steel.

Conclusions

We have shown that commercially available electromagnetic simulation software can be used to accurately predict the impedance signature of an encircling coil used to interrogate metallic objects housed within a nuclear material storage container. An existing coil and AT-400R container employed in previous research at PNNL were re-used to validate the simulations. The enhanced understanding provided by this type of simulation capability enables PNNL to optimize the design of the EM coil sensors and optimize the conditions under which the sensing should occur.

Simulations can also be used to develop new coil sensors targeted for container or cargo inspection. Current research is underway to investigate the feasibility of using the coil signature method to inspect artillery canisters, marine vessel and airplane cargo containers, and railcars. In regards to arms control and treaty verification, the simulation tool can be used to optimize the design of nuclear material storage containers so that new attribute measurement systems with information barriers (AMS/IB) or standalone signature methods can be developed.

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A. Mark Jones is a senior research scientist at the Pacific Northwest National Laboratory (PNNL). He received the B.S. and M.S. degrees in electrical engineering from North Carolina State University in 1998 and 1999, respectively. His graduate research included electromagnetic modeling of power electronics components at the NCSU Electric Power Research Center. Prior to joining PNNL in 2009, he worked with advanced electromagnetic applications in engineering positions with Harris Corporation and Ansoft Corporation. His current work involves the use of high-frequency and low-frequency electromagnetic simulation tools to design systems for national security applications. Jones is a senior member of IEEE and has served as chair of the IEEE Melbourne AP/MTT Chapter and as secretary for the IEEE Oregon MTT Chapter.

Kyle Bunch is a registered professional engineer who has a Ph.D. in electrical engineering with an emphasis on computational electromagnetics, simulation, and power systems. His graduate work was co-sponsored by the Air Force and Hughes Aircraft Company under the Air Force Thermionic Research Program at the University of Utah. He has worked at the Electron Dynamics Division of Hughes Aircraft in Torrance, California USA, as well as TRW Space and Defense in Redondo Beach, California USA. He also served as a research assistant professor where he taught courses in EE and pursued research in the area of high-frequency devices. His recent experience includes being a researcher at Sandia National Laboratories and most recently a senior research scientist at Pacific Northwest National Laboratory. He is a senior member of the IEEE and has served as Chair of the Utah Section of the IEEE as well as Publications Chair for the 2008 IEEE Nanotechnology Conference.

Pamela Aker is a senior research scientist in the Applied Physics Group at PNNL. She received her B.S. and Ph.D. in chemistry from Carleton University, Ontario, Canada in 1980 and 1986, respectively. Prior to joining PNNL in 2002, she was an assistant professor of chemistry at the University of Pittsburgh from 1992 to 2000, and a senior optical engineer with Tellabs from 2000 to 2002. Her current work involves developing optical based sensors for national security applications and free space optical communications for data exfiltration.

The IAEA Workshop on Requirements and Potential Technologies for Replacement of ^{3}He Detectors in IAEA Safeguards Applications

Mark M. Pickrell and Anthony D. Lavietes
International Atomic Energy Agency, Vienna, Austria

Victor Gavron, Daniela Henzlova, and Howard O. Menlove
Los Alamos National Laboratory, Los Alamos, New Mexico USA

Malcolm J. Joyce
Lancaster University, Lancaster, UK

Richard T. Kouzes
Pacific Northwest National Laboratory, Richland, Washington USA

Abstract

The International Atomic Energy Agency (IAEA) held an international workshop March 22–24, 2011, to address the question of a possible replacement for helium-3-based neutron detectors. Within this wider scope, the workshop was focused on those applications used in IAEA verification activities. There were two principle objectives of the workshop: 1) to determine the specific requirements that a potential replacement technology would have to satisfy, and 2) to identify alternative detector technologies that appear promising for meeting those requirements. The workshop was successful in achieving both objectives. A set of detailed and quantitative specifications was developed and achieved a general consensus among the conference participants. These included operational considerations such as temperature stability, safety, weight, and cost in addition to a number of performance requirements. The performance requirements were derived from an analysis of the spectrum of IAEA applications that use neutron detectors. After analyzing these applications, it was determined that the most common application for ^{3}He detectors was for neutron coincidence counting, comprising over 95 percent of ^{3}He use. The details and rationale for this assessment will be provided. The performance requirements for neutron coincidence counting can be directly calculated from the standard variance expressions. From these, a basic figure of merit (FOM) was developed that can be used to rank various different options. For neutron coincidence counting, the figure of merit is: $\varepsilon/\sqrt{\tau_D}$, where ε is the detection efficiency and τ_D is the detector die-away time. Both the FOM and the calculations will be presented. The full list of requirements is included in this paper. The second purpose of the workshop was to identify promising replacement technologies. There were multiple presentations of candidate detection technologies over the course of the workshop, covering a wide spectrum of approaches and detection physics. These technologies were judged relative to the performance of a ^{3}He-based system, as well as its ability to meet the replacement technology requirements as developed in this workshop. The paper will present a summary of this assessment.

Introduction

Neutron detectors are a vital component for the implementation of IAEA safeguards. The IAEA uses neutron detectors for both nondestructive assay (NDA) of nuclear material (quantification) and for detecting the presence of radioactive items (item accounting). Gamma-ray measurements are also used for these applications, but in many cases neutron emission is significantly more effective. Neutron radiation is more penetrating than gamma rays and consequently there are multiple applications, particularly for large items, where a neutron measurement is essential. Neutrons may also provide a more unambiguous method for monitoring nuclear materials, as there are many isotopes that produce gamma radiation, but only alpha-emitting actinides (through the alpha-n reaction) and fission produce neutrons in quantity.

Neutron detectors based on ^{3}He comprise essentially all practical neutron detectors for both IAEA Safeguards and State Systems of Accounting (i.e., domestic safeguards). The performance parameters of ^{3}He neutron detectors are superior to present alternatives for most applications. First, ^{3}He provides a simple and robust mechanism for conversion of the reaction energy to an electronic pulse. The reaction formula in a standard ^{3}He pro-

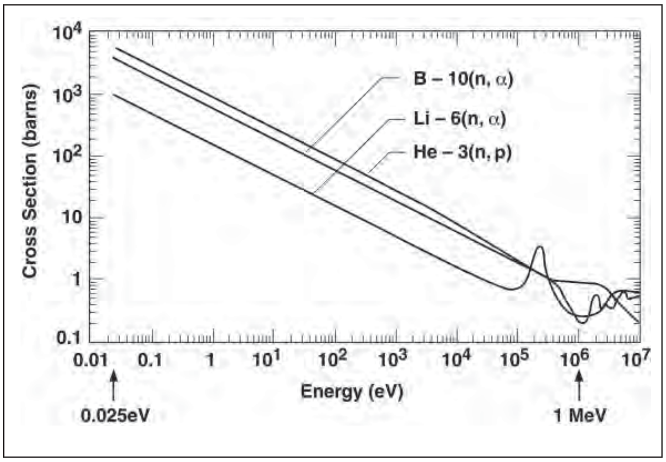


Figure 1. Neutron absorption cross-sections for several isotopes as a function of incident neutron energy. ^{3}He has the highest cross-section for neutron energies less than ~10^5 eV.

portional counter is: $n + {}^3\mathrm{He} \rightarrow {}^3\mathrm{H} + p$. The energetic proton and triton both ionize the gas in a proportional counter, which is collected and amplified to form an electronic pulse. This technology is simple, easily understood, and mature. Second, the cross-section for the ^{3}He neutron absorption reaction is the highest for any of the neutron detection isotopes, with the exception of gadolinium, which produces only a gamma ray from the reaction, which significantly complicates its use. Therefore, ^{3}He detectors have arguably the highest detection efficiency of practical gas-based detectors. Figure 1 shows the relative cross-sections for the common neutron detection isotopes. These are limited to those producing an ionized particle from the reaction and as can be seen in the graph, ^{3}He has the largest cross-section. Finally, the reaction energy for ^{3}He is large, much larger than the likely kinetic energy of the incident neutron, so that the signal produced by neutron detection is independent of neutron energy.

Neutron detectors based on ^{3}He are used throughout the full spectrum of deployed nuclear material measurements. This extensive application set is based on the "Point Model" theoretical hierarchy for correlated neutron measurements. The point model was developed in two parallel, independent derivations: one by Bohnel,[1] the other by Hage,[2] and Cifarrelli.[3] A sample of nuclear material that is to be assayed emits neutrons that are somewhat stochastic and somewhat correlated in time. This understanding is apparent when considering that all prompt neutrons emitted from a fission chain (initial fission and all subsequent induced fissions) are necessarily time-correlated because they are emitted essentially simultaneously (for relevant time scales). By contrast, initial spontaneous fissions or alpha-n events occur entirely at random. The point model provides a mechanism for extracting the time-correlated component of this neutron pulse stream.

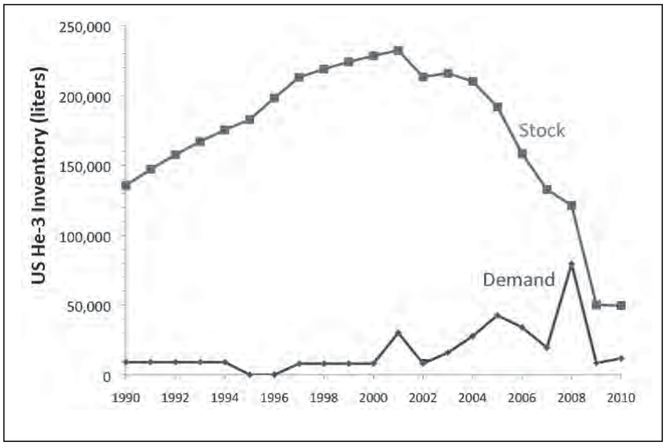
The mathematics of the Point Model specifies that the correlated information is expressed as the factorial moments of the neutron probability distribution. These correlated moments are conventionally termed: singles, doubles, and triples because they can be thought of as occurring as single neutrons, neutron pairs, or neutron triples. They can be measured by an electronic instruments called a *shift register*. A shift register is simply a class of electronics instrument that effectively preprocesses the neutron detector pulse stream in real time to determine the first three factorial moments of the neutron pulse stream.[4]

We note parenthetically that there is a second theoretical framework for analyzing the time correlation of a neutron pulse stream: Feynman Variances.[5] The Feynman Variance approach has the same purpose as the Point Model, namely, reducing the time correlation data of a neutron pulse stream to a quantitative assay. Both theoretical models have been studied extensively and also compared. The Feynman Variance method is equivalent to using only the random-triggered signal from the shift register. A detailed mathematical comparison demonstrated that these two theoretical systems are equivalent.[6,7] Both methods were shown to produce the same assay result and both have the same resultant uncertainty.[8,9] Therefore, both systems have achieved an optimum for extracting the correlated information, as it is extremely unlikely that two entirely disparate mathematical models would achieve the identical results unless both were at an extremum. However, the Feynman Variance implementations require time-tagged or *list mode* data acquisition and all analysis is done as post processing. This approach contrasts with the Point Model system, which uses a shift register to pre-process the data in real time. The shift register method is the only system in widespread use for safeguards.

The family of instrumentation that implements shift register electronics includes a variety of commercially available shift register modules, several commercially available detector preamplifiers, and several commercially available detector tubes filled with ^{3}He gas. These detectors and electronics are fully compatible with each other, providing a mature technological, as well as theoretical, infrastructure. Any presumptive replacement technologies for ^{3}He detectors must be fully compatible with the Point Model and thus with the shift register implementation.

The unique effectiveness of ^{3}He for a wide array of neutron detection applications has generated a great demand for this technology in safeguards, waste assay, and nuclear security. There are also several medical and scientific applications. Unfortunately, the supply of ^{3}He is dwindling and the demand far exceeds production. Existing stockpiles will likely be consumed in the next few years if present trends continue. Already there have been large increases in the price for ^{3}He in the open market. The U.S. government (a primary ^{3}He supplier) has severely reduced allocations for safeguards, and IAEA safeguards in particular, creating uncertainty for future gas availability. This uncertainty, combined with the eventual depletion of existing stockpiles, places IAEA safeguards measurements at risk. Without an adequate, assured supply of ^{3}He (or an effective replacement), IAEA safeguards in

Figure 2. Helium-3 supply, demand, and existing stockpile. Note that the existing stockpile is nearly depleted. (With permission from Steve Fetter, "Overview of Helium-3 Supply and Demand."[12])



particular (and worldwide safeguards in general) will be significantly impaired.

Present production of ^{3}He from tritium decay of U.S. stockpiles, as reported by the U.S. Department of Energy, is about 8,000 liters at standard temperature and pressure (STP) per year. The demand for ^{3}He is now projected at between 10,000 and 18,000 liters at STP per year.[10] The deficit must be supplied from the existing stockpile, which is approximately 31,000 liters. These figures assume that no additional ^{3}He will be used for nuclear security applications (e.g., for portal monitoring). Figure 2, from the U.S. Office of Scientific and Technology Policy, depicts the problem.[11] The production, use, and inventory are shown for the past two decades. As is evident, the stockpile has nearly been depleted, subsequent to the 9/11 event and the dramatic increase in the use of ^{3}He for portal monitoring plus usage for neutron scattering science. The U.S. government has decided to cease ^{3}He allocations for nuclear security portal applications, which reduces the demand. However, the residual demand remains above the replacement rate and the existing stockpile will soon be depleted. In the absence of reliable data on the gas availability from other sources (e.g., other weapons states, states employing heavy water reactors, etc.), one can use the U.S. data as the best available illustration of the global trend in ^{3}He availability. Therefore, replacement technologies must be identified to assure that IAEA safeguards (and worldwide safeguards in general) can be assured for the future.

To address this concern, the IAEA hosted an international workshop March 22-24, 2011. The purpose of this workshop was to determine whether an alternative technology could be identified within a reasonable timeframe that would have neutron detection performance nominally equivalent to ^{3}He-based systems. The intent was to address the specific measurement needs of the IAEA. However, the following analysis can be generalized to the broader problem of neutron-based nondestructive assay for other safeguards applications, waste characterization, and nuclear security.

The reason for the particular focus on IAEA measurement needs was scientific, not institutional. There is a considerable worldwide scientific effort to develop novel neutron detection methods and materials. These efforts address a wide array of scientific and technological issues. However, not all of these incipient technologies will be an effective replacement for ^{3}He for safeguards measurements. Not all of these novel technologies will be compatible with the Point Model measurement methods and the associated technological infrastructure. Therefore, while they may have other benefits and applications, they may not necessarily contribute to the solution of the IAEA measurement problem.

The IAEA Neutron Measurement Requirements

Analysis Rationale

The approach adopted for the deliberations during this workshop was to partition the problem of determining a replacement for ^{3}He. First, we separately considered the formal determination of the requirements for a ^{3}He replacement, and the descriptions of the technologies that were available or promising. The consideration of IAEA requirements was divided further into those applications that were sufficiently difficult to require the full capabilities of ^{3}He and those that were not as technically demanding and could immediately be accommodated using existing alternative technologies. This division was based on application measurement requirements and possible replacement technology capabilities as indicated by the neutron absorption cross-sections listed in Figure 1. Boron-10 (^{10}B) has the next highest neutron absorption cross-section and many organizations have developed or are developing detection systems using this isotope in many forms. From the perspective of a direct replacement of ^{3}He tubes, ^{10}B-coated tubes are commercially available and can be fabricated to the exact dimensions of a ^{3}He tube. ^{10}B-coated tubes also exhibit an operational behavior that is similar to a ^{3}He tube and is reasonably compatible with the current infrastructure utilized for ^{3}He. The fundamental difference between ^{10}B and ^{3}He tubes is the significantly lower detection efficiency of ^{10}B because of several factors: lower neutron absorption cross-section, geometric effects, detection mechanism differences, and lower relative ^{10}B content. Additionally, ^{10}B detectors have approximately the same gamma sensitivity as ^{3}He-based detectors. For those applications that are less challenging, namely those that do not require as high a neutron detection efficiency, ^{10}B tubes could be a ready replacement for ^{3}He. A typical example of a less challenging application is a neutron flux monitor, which is used to detect the presence of an item emitting a large neutron flux, but is not used for material assay. Advances have been made to address low detection efficiency by increasing boron surface area and high density designs that implement tubes of small diameter or layered parallel plates have been developed. These could be more suitable for the more demanding applications. Finally, the requirements for challenging measurement applications were partitioned into operational considerations and optimization considerations. In broad terms, the operational considerations are the engineering requirements necessary to operate the detector safely and reliably in a nuclear facility. The optimization requirements are those parameters that enable the neutron detector system to provide the highest accuracy measurement possible, given constraints of cost, size, and safety.

This analysis was conducted in four stages:

1. From the complete ensemble of IAEA neutron detector applications, those that could easily be replaced by existing technologies were separated from those applications that require the full capability presently only provided by ^{3}He detectors. For example, several IAEA applications use neutron coincidence or multiplicity counting and require high performance ^{3}He detectors. Applications that measure only the total neutron flux do not require these high performance detectors.
2. Applications requiring the higher ^{3}He detector performance were then evaluated. There were only two principal applications in this category: neutron coincidence counting and neutron multiplicity counting. Then, the list of individual applications was evaluated, which established that >95 percent of these applications were for neutron coincidence counting. Multiplicity applications were relatively rare.
3. The requirements for neutron coincidence counting application were analyzed for both performance requirements that affect the measurement precision and bias, and operational requirements that address safety and deployment issues in a functional nuclear facility. Most of the operational requirements were quantifiable and limiting values could be established. The performance requirements were also quantified as a figure-of-merit (FOM) such that any candidate replacement technology could be directly compared to the corresponding FOM for ^{3}He detectors.
4. Finally, the requirements matrix was compared to the performance characteristics of several promising replacement technologies. Multiple presentations were provided during the workshop that proposed candidate technologies for consideration as a suitable ^{3}He replacement. The performance of these technologies compared to the IAEA requirements suggests that several of these candidate technologies may quickly evolve into viable ^{3}He detector replacements. Some of the more attractive candidates are presented later in this paper.

By accounting for all declared nuclear material, the IAEA assures that no nuclear material in a member state's nuclear facilities is diverted. This accountancy is achieved by two distinct mechanisms: item counting and material accountancy. Item counting, as its name implies, maintains a continuity of knowledge of individual items known to contain nuclear material. The exact amount of material contained within the item is not specifically relevant to the safeguards conclusion as long as the item remains intact and can be identified. A typical example would be the tracking of spent fuel bundles from CANDU-type reactors. These fuel bundles are monitored from the time they are extracted from the reactor calandria until they reach permanent dry storage containment. Continuous long-term monitoring of the dry storage ensures that the spent fuel bundles remain secure. Much of the monitoring of nuclear material *items* is done using the agency's containment and surveillance (C&S) technology, typically video cameras and seals. In many cases, C&S is complemented with the use of radiation detectors to establish, unambiguously, the presence of an item. Both neutron and gamma-ray radiation is used for item detection. In these applications, there is no need to quantify the amount of radiation; as it is sufficient to detect a large radiation flux to unambiguously establish the presence of the accountancy item. Moreover, in most cases, the radiation emission is sufficiently strong that high detection sensitivity is not required. Indeed, the IAEA has implemented fission chambers extensively for this application and in some cases substituted ^{3}He detectors because they were less expensive. Fission chambers are very robust and highly immune to gamma-ray interference. Drawing from earlier deliberations, the boron-lined proportional counters may be able to satisfy the requirements of this application in addition to traditional fission chambers. Additionally, the ^{10}B-lined proportional counters will still have to meet all operational requirements outlined later in this paper to satisfy the engineering requirements for safety and reliability. However, the detector performance is not as critical because there is sufficient neutron flux and no assay requirement, only the detection of a particular item.

The more challenging requirements are associated with detectors intended for material assay applications, which involves the quantification of material rather than simple item detection. Moreover, some of the agency specifications for NDA require total measurement uncertainty (accuracy) of 1 percent. Achieving such an exact measurement is much more technically challenging and is typically performed with neutron coincidence or multiplicity counting. The rate of neutron detection scales with detection efficiency, ε^1, however, the coincident neutron rate scales as ε^2 and the multiplicity triples rate scales as ε^3. Therefore, coincidence and multiplicity measurements are much more sensitive to the efficiency parameter than simple detection, which is based on singles (or gross) neutron counting. Finally, as the accuracy of these assay measurements can be fairly stringent, other performance aspects of the detection system must be optimized (e.g., detector die-away time).

The workshop deliberations addressed the question of the dominant method employed for neutron-based assay. In this simple analysis, the inventory of neutron instruments was evaluated and it was determined which instruments were used for coincidence measurements and which instruments were capable of multiplicity counting. A number of assessment methodologies were considered, including an assessment of the total number of assays rather than the number of instruments themselves. Another approach would be to consider the total quantity of data produced by either method. The method adopted for the assessment was to count the number of instruments, as it was reasonably representative and simple. As noted earlier, 95 percent of IAEA neutron assay systems are coincidence counting based. Moreover, if total assays conducted were also included in the assessment, the percentage would be higher, as coincidence systems are the only detectors in this family that operate in unattended and continuous mode. The conclusion is that neutron coincidence counting of nuclear material is the predominant application for ^{3}He-based detectors for the assay of nuclear material, and therefore, the parameter selection for a presumptive replacement detector technology should be based on this application.

In the following two sub-sections, the results of the workshop deliberations are presented on the necessary performance specifications for a presumptive ^{3}He replacement technology. These requirements are divided into Operational Requirements, which outlines the engineering requirements necessary for safe, robust, and practical deployment in a nuclear facility, and Figure of Merit, which derives a figure of merit to compare the performance of candidate replacement detector technologies against that of ^{3}He.

Figure of Merit

A Figure of Merit (FOM) for neutron NDA can be derived from the Point Model theoretical hierarchy on which neutron-based assay relies, and the assessment conducted at the workshop, which established the principal applications for neutron assay by IAEA Safeguards. The workshop concluded that the safeguards problem of item detection and counting can be achieved with the comparably lower performance of existing technologies, for example existing ^{10}B-based detectors. The workshop also concluded that the more challenging problem was neutron-based assay, which requires neutron coincidence or multiplicity counting.

The assay will be based on the Point Model framework, as it is the basis for all IAEA safeguards measurements and is the most widely used method for analyzing correlated neutron data. Therefore, the FOM will be developed to optimize either neutron coincidence counting or neutron multiplicity counting, as those are the only two assay methods that meet these conditions. In addition, the focus of the FOM will be on neutron coincidence counting, because that constitutes the overwhelming majority of IAEA neutron assay applications. Finally, the basis for the FOM for neutron NDA will be the accuracy of the measurement, as the purpose is a material assay rather than item detection. Furthermore, the FOM will be based on the *precision* of the neutron measurement rather than the bias. Bias error does not depend strongly on ^{3}He detector characteristics; it is mostly dependent on the sample size, geometry, material, and system calibration. By contrast, the measurement precision depends very strongly on the detector parameters, as well as other factors that can be held constant. Therefore, the development of an expression for detector FOM will be based on those detector parameters that affect the precision of the neutron coincidence measurement with other factors being held constant.

An ancillary benefit to developing a FOM for the precision of neutron coincidence counting is that it affords the ability to derive closed-form expressions. This approach is not possible (at present) for neutron multiplicity counting. We will augment the analytical expressions with numerical calculations for both neutron multiplicity and coincidence measurements. These numerical calculations use the Ensslin Figure of Merit code (EFOM), which uses the full expansion of multiplets to calculate the coincidence and multiplicity precision.[13] Although the closed form expressions for precision only apply to coincidence counting, we will show numerical results that demonstrate that multiplicity counting would be optimized as well (i.e., if the parameters are selected to optimize the coincidence measurement, the multiplicity measurement would be nearly optimized as well).

There are two fundamental parameters for a ^{3}He neutron detector that will form the basis of the figure of merit and need to be defined carefully: the detector efficiency, ε, and the detector die away time, τ_D. In the Point Model, the detector efficiency is defined as the total likelihood that an emitted neutron from a source will be detected by the detector. However, this is an extrinsic variable and depends on the detector geometry (e.g., whether the detector covers 4π, for instance). However, in the context of a detector parameter, the more relevant parameter would be the intrinsic efficiency, which is defined as the likelihood that a single neutron that impinges on the detector surface will be detected. This definition is independent of system geometry and will be the meaning of efficiency used here for the FOM. The second parameter is the die-away time, which describes a process that applies only to moderated neutron detectors; it would not apply to fast neutron detectors such as liquid scintillators, for example. Die away time is the characteristic lifetime of neutrons in a moderated detector after they have been moderated. It describes a typically exponential decay. The loss mechanisms are detection, absorption by the hydrogen moderator, or the neutrons diffuse out of the detector entirely. The transport mechanism for these processes is diffusion; after neutrons are moderated, they typically diffuse to the ^{3}He detectors or to hydrogen capture or leakage.

In the case of fast neutron detectors, neutrons are not moderated and therefore, they do not diffuse to the detector. They are detected immediately or not at all. However, in the context of the Point Model the die away time is still a relevant parameter when used for a figure of merit. When a thermal (i.e., ^{3}He based) neutron detector is optimized, the gate width for the coincidence circuit is a fixed constant times the die away time. Nominally, the constant is approximately 1.2, but this can vary with measurement conditions and counting rates. For the purposes of a detector figure of merit, it is sufficient to take: $\tau_D \approx G$, namely the die away time is equivalent to the gate width. Since a fast neutron detector must support the Point Model infrastructure, specifically the Shift Register electronics, fast detection systems will operate with a fixed gate width and this can be substituted into the figure of merit formalism.

Beginning with the equation for the relative precision for a neutron coincidence measurement:

$$\sigma_{rel} = \frac{\sqrt{(R+A)+A}}{R} \qquad (1)$$

where *(R+A)* is the number of counts in the signal-triggered shift register gate and *A* is the number of counts in the random triggered gate.

Substitute for these the doubles and singles rates:

$$R = \dot{D}t \text{ and } A = Gt\dot{S}^2$$

$$\sigma_{rel} = \frac{\sqrt{\dot{D}t + 2Gt\dot{S}^2}}{\dot{D}t} \qquad (2)$$

The values for the doubles rate, $\dot{D}$, and the singles rate, $\dot{S}$, are obtained from the Point Model equations for doubles and singles.[14]

$$\dot{S} = F_0 m\varepsilon M \nu_{s1}(1+\alpha)$$

$$\dot{D} = \frac{F_0 m\varepsilon^2 f_d M^2}{2}\left[\nu_{s2} + \left(\frac{M-1}{\nu_{i1}-1}\right)\nu_{s1}(1+\alpha)\nu_{i2}\right] \qquad (3)$$

where:
t = time
F_0 = fission rate
ε = detection efficiency
f_d = doubles gate fraction
M = leakage multiplication
G = shift register gate width
α = ratio of alpha-n produced neutrons to fission neutrons
ν = fission multiplicity constants.

Consider the term inside the radical in Equation 2. When the mass, *m*, is small, $\dot{D}t >> 2Gt\dot{S}^2$ because $\dot{D}$ scales as *m* and $\dot{S}^2$ scales as m^2. For the low mass case, Equation 2 simplifies to:

$$\sigma_{rel} = \frac{\sqrt{\dot{D}t}}{\dot{D}t} = 1\Big/\sqrt{\dot{D}t} \qquad (4)$$

Insert the expression for the doubles rate from Equation 3, set M=1, and assume all other physical constants and measurement parameters are fixed. Then the relative error becomes:

$$\sigma_{rel} \propto 1\big/\varepsilon \qquad (5)$$

Now consider the converse condition: the high mass case, so that: $\dot{D}t << 2Gt\dot{S}^2$. Following the same procedure as above, and assuming that the gate width is optimized so that $\tau_D \approx G$, the relative error becomes:

$$\sigma_{rel} \propto \frac{\sqrt{\tau_D}(1+\alpha)}{\varepsilon\sqrt{t}} \propto \frac{\sqrt{\tau_D}}{\varepsilon} \qquad (6)$$

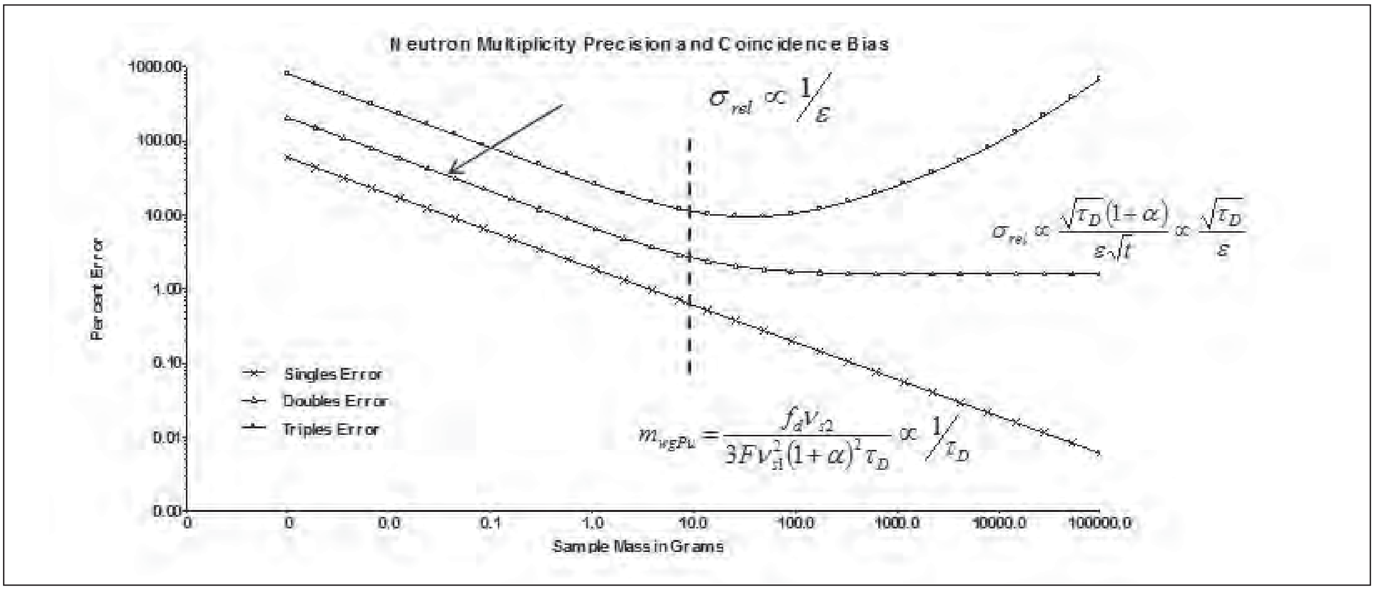
Finally, consider the condition that: $\dot{D}t = 2Gt\dot{S}^2$ to define the position of the knee of the curve. Setting M = 1, assuming the gate width is optimized to the die away time so that: $\tau_D \approx 3\big/4\,G$, and solving for mass:

$$m_{wgPu} = \frac{f_d \nu_{s2}}{3F\nu_{s1}^2(1+\alpha)^2\tau_D} \qquad (7)$$

These equations form the basis for establishing a figure of merit for presumptive replacements for ^{3}He detectors. Alternatively, we can view the same result by considering a numerical calculation. In Figure 3, we calculate the relative precision for the singles, doubles, and triples using the Ensslin Figure of Merit code (EFOM). Nominal assay values of α = 1, M = 1, ε = 50 percent, and a die away time of 50 microseconds are assumed. The middle curve is the precision for coincidence counting. The expressions for coincidence precision just derived and valid for the curve extremes are annotated on the figure. Also shown is the value for the *knee* of the curve, Equation 7. This plot shows clearly that there are two regions for the determination of the relative error, one for low mass and the other for higher mass, as derived above.

The Figure of Merit for a presumptive replacement for a ^{3}He detector can be proposed based on the results plotted in Figure 3. We assume the high mass case because safeguards is concerned with larger masses, (as contrasted, for example, with

Figure 3. Relative precision for singles, doubles, and triples calculated from Ensslin Figure of Merit code. Nominal assay values were assumed and multiplication was stipulated to be unity. The expressions for the precision for doubles (coincidence counting) are annotated on the figure.



a waste measurement that might be dominated by the low mass case). As discussed above, the natural FOM is simply the inverse for the relative precision. Thus:

$$FOM \equiv \varepsilon / \sqrt{\tau_D} \tag{8}$$

There are several conditions that must also be considered when using this FOM to compare a replacement detector to a ^{3}He detector. First, the efficiency, ε, used in the Point Model, Equation 3, refers to the total system efficiency because that is the basis for the model. However, the efficiency in Equation 8 is detector efficiency and refers to the intrinsic efficiency (e.g., capture probability in each detector element, detector element response time). Second, the values of efficiency and die away time will vary considerably among ^{3}He detectors and these variations depend principally on the size and respective cost of the ^{3}He detector under consideration. The die away time is an extrinsic property of the detector system, influenced by the design of the system; number of detector elements per unit volume, moderator design, and the overall size of the system that affects the neutron escape probability and timing. When comparing potential replacement detector technologies to ^{3}He, the comparison must be fair, therefore, the detector size and cost should be nominally the same for the replacement as for the particular ^{3}He detector configuration.

Finally, when matching the detector areas, the total area of the detector has to be considered rather than just the active area. A practical detector has to fit together to provide a full enclosure geometry in many cases. Geometrical effects may force the detector face to include some of the non-active area; therefore, the FOM should be evaluated at fixed total detector area.

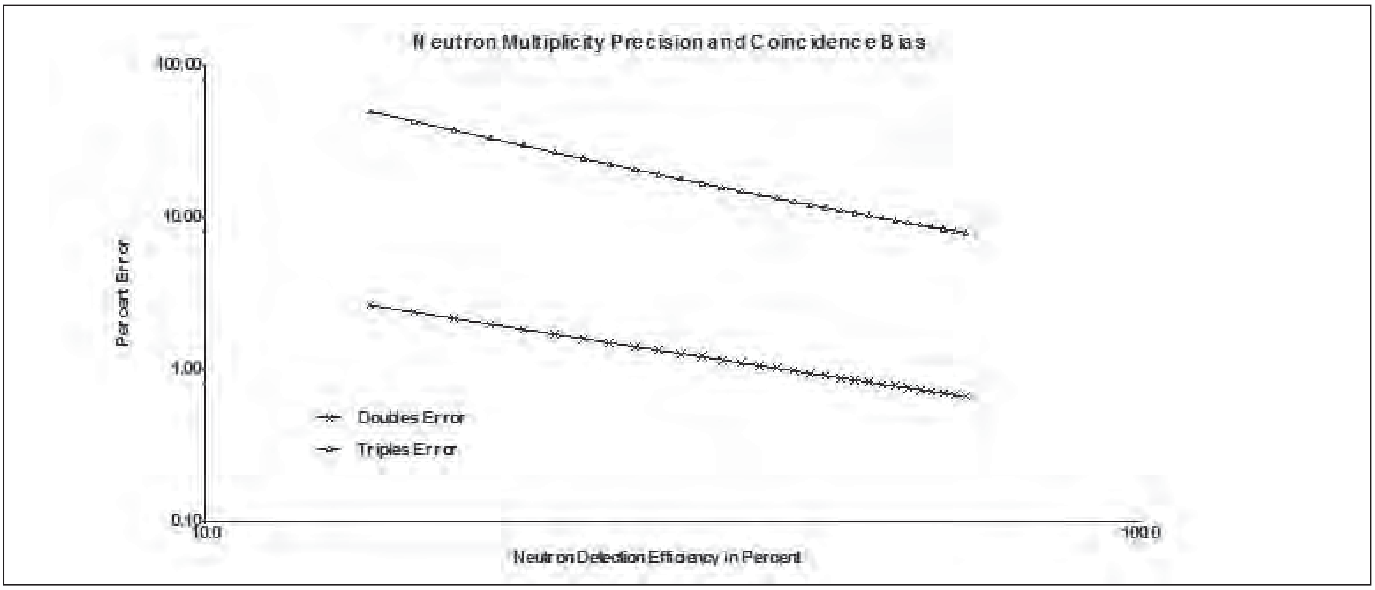
Although the FOM equations were derived for the coincidence counting case, as that represents the overwhelming fraction of IAEA applications, the FOM expression, Equation 8, is equally true for multiplicity counting as well. This assertion can be shown numerically. Figure 4 below shows a calculation from the EFOM code for the relative assay precision for the doubles and triples. Nominal assay parameters are assumed and the efficiency is varied from 15 percent to 55 percent (the nominal range for ^{3}He detectors). The efficiency is in the numerator of the FOM expression. Note that the relative behavior is the same.

Equation 8 and the conditions specified in the Operational Requirements section provide a quantitative basis for the direct comparison of candidate replacement technologies to the existing ^{3}He detector capabilities.

Operational Requirements

The following are specific operational requirements for replacement neutron detector technologies that were identified and quantified during the workshop. Each was identified as essential for safe, robust, reliable, and practical operation within a nuclear facility. The quantification was also largely based on the present capability of nominal ^{3}He-based neutron detection with polyethylene moderation. Many of these requirements apply to any replacement technology, though some cases only apply to the more stringent assay application. In each case, this distinction will be made.

Figure 4. Doubles and triples relative precision for nominal assay parameters varying with detector efficiency (the numerator in the FOM). Both behave in a similar fashion.



Intrinsic Efficiency

Intrinsic efficiency is defined as the probability of detection of a single neutron that enters a detector front surface. The front surface is defined to include both active and inactive regions, so that detectors can be compared on equal terms. Intrinsic efficiency is a principal factor of the figure of merit expression, but for any detector to operate, there has to be a minimum value. The minimum detection efficiency has been determined to be 1 percent for IAEA applications.

Gamma Discrimination

Neutron assay systems operate in environments with both neutron and gamma ray fluxes. In order to measure the neutron flux unambiguously, the detector must be highly resistant to interference from gamma rays. A typical problem with neutron detectors is that significant gamma ray pileup in the detector can cause false neutron counts. At sufficiently high flux, gamma rays can cause a significant contribution to the observed neutron count rate, and consequential error. The effect on ^{3}He tubes tends to be a threshold effect. The interference from gamma rays is very small, that is, below detectable levels, until the threshold is surpassed, at which point the gamma ray interference can be comparable to the neutron signal. An advantage of pulse threshold gamma ray discrimination is that the gamma ray separation is not count rate limited. This effect is illustrated in Figure 5 below.[15] Gamma ray fluxes below 100R/hr will not produce any interference for normal operating voltages in 4 atm 254 mm long ^{3}He tubes.

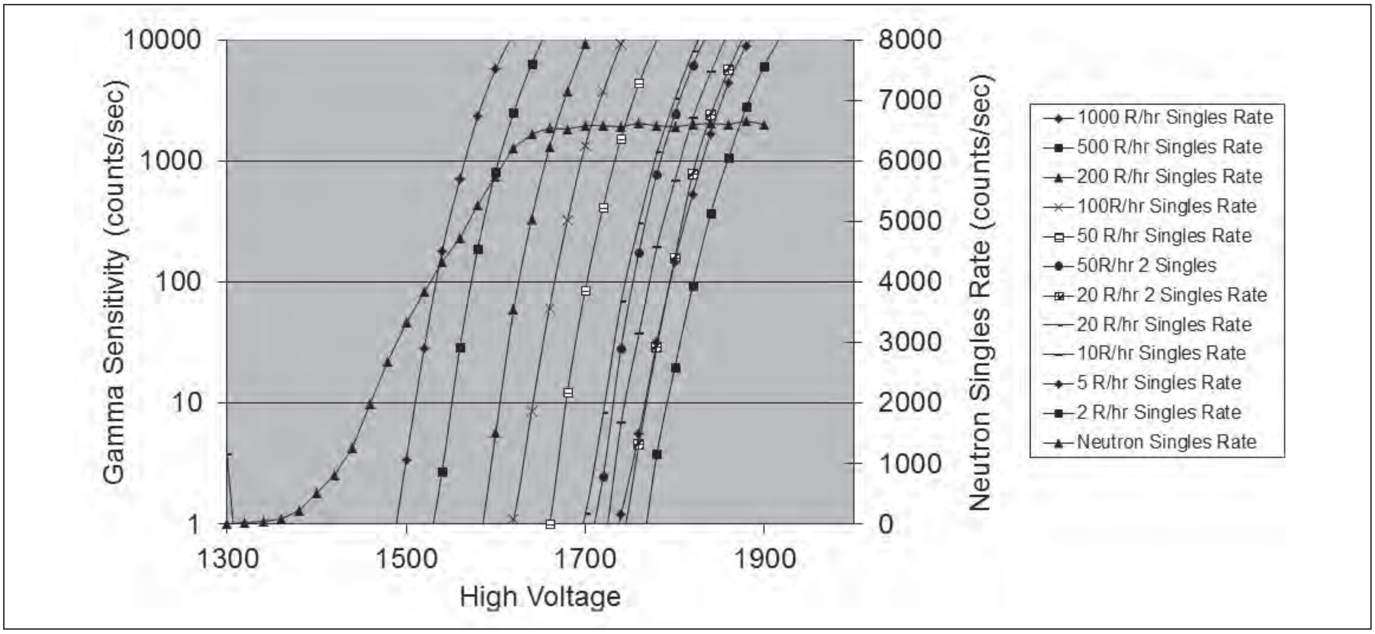
Maximum Neutron Count Rate

Many applications require measurements of items that have a very high neutron emission (e.g., large sample sizes in processing plants and irradiated fuel). A replacement neutron detector must be able to accommodate these fluxes to be effective in the full range of applications. The count rate for ^{3}He detectors is limited by two primary mechanisms: the tube recovery time, which is the time required for the ionized particles created by a neutron capture event to be swept out by the radial electric field, and saturation rate the detection rate at which the electric field begins to collapse due to significant ionization within the gas volume. The typical tube recovery time for a ^{3}He tube is about 1 to 3 microseconds, but the saturation rate is typically about 50kcps/tube. The limiting detection rate for a single tube is typically limited by the saturation rate. Therefore, considering the nominal size of ^{3}He tubes (about 1 inch diameter), and nominal tube spacing pitch of about 5 cm, the maximum tolerable neutron flux is about $100\ {}^{\text{counts}}\!/_{\text{sec}-cm^{2}}$. A replacement technology should perform at this level or higher, or it may be limited to only a subset of possible applications.

Maximum Tolerable Gamma Ray Flux

The maximum tolerable gamma ray dose specifies the amount of absorbed dose until failure of the detector. Existing ^{3}He detectors, including associated electronics, have demonstrated survivability up to 1 MGy of absorbed dose.[16] A competing technology should at least approach this value, within considerations of the overall operating environment.

Figure 5. Gamma ray sensitivity for a ^{3}He tube and a PDT-10A amplifier for different bias voltages and gamma ray flux rates. The left axis corresponds to ^{137}Cs gamma pileup counts, and the right axis corresponds to a ^{252}Cf source. Below 1 Gy (100 R)/hr, the interference is negligible for normal operating voltages. A representative standard plateau curve ("Neutron Singles Rate") is included for reference.



Commercial Availability

Commercial availability is simply the requirement that the IAEA can procure the necessary technology. A technology that is available only as a laboratory experiment does not address the central issue of finding a replacement for ^{3}He detection. Moreover, the supply of ^{3}He is dwindling rapidly and will be depleted within just a few years at present rates of consumption. Therefore, replacement technologies must be available within the next two to three years.

Robustness

Robustness is a measure of the engineered quality of a system and its resilience under normal operating conditions. This parameter has a direct effect on overall reliability, but classic reliability is typically measured under controlled conditions in a laboratory. Robustness, by contrast, addresses actual deployment conditions and establishes whether the equipment can maintain the reliability under harsher conditions than the controlled conditions of a laboratory. In the interest of setting standards for robustness, the IAEA has been moving towards using formal engineering standards for all agency equipment as a mechanism to ensure that all equipment is designed and built to the highest engineering levels possible. This method also establishes a consistent engineering approach and level of quality across the entire IAEA equipment inventory. In the case of ^{3}He detector systems, the IAEA has already specified U.S. Military Standard 810F, Method 514.5, Procedure II and Method 516.5 (vibration, seismic, and shock specifications). Presumptive replacement technologies will also have to meet these or similar requirements.

Reliability

Reliability is specified by the conventional parameter: Mean Time Between Failures (MTBF). It assumes a constant probability in time for routine failure, and so it explicitly excludes the "infant mortality" of newly built systems and the end-of-life mechanisms for failure. The MTBF of ^{3}He detectors is difficult to calculate because there are no known failures to date in the history of ^{3}He tube implementations for safeguards applications. While not readily noted in the literature, manufacturers of ^{3}He tubes indicate an MTBF in excess of 650 years. Given the historical experience and the manufacturer information, the MTBF of a ^{3}He tube has no negative impact on system reliability and is not significant. In a relative sense, a sufficient reliability measure for a replacement technology would require an MTBF that would have an insignificant impact on overall system reliability. A conservative approach indicates that an MTBF specification of 100 years would provide a sufficient reliability, but in any case it should significantly exceed respective figures for the MTBF of the amplifier systems, power supply systems, and other auxiliary components.

Consistent with Existing Analysis

A replacement technology must be compatible with the existing theoretical hierarchy used for neutron counting and its attendant electronic instrumentation. Therefore, it must be compatible with analysis by the Point Model theoretical construct and shift register data acquisition technology. Specifically, the output signal of the detector/preamplifier system must be a TTL digital pulse, nominally 5 volts in amplitude, 50 nanoseconds wide, with a separation between pulses of at least 20 nanoseconds.

Temperature Stability

Existing ^{3}He-based neutron coincidence assay systems achieve a measurement precision of better than 1 percent, which is comprised of several components from different measurement effects. The temperature dependent variation is only one of these components and should be relatively small so as to not significantly contribute to the total system error. Specifically, ^{3}He detector systems have a temperature coefficient of between $0.01 \%/_{^\circ C}$ to $0.03 \%/_{^\circ C}$. The temperature coefficient is a combination of several effects that go in opposite directions to partially cancel each other. The largest temperature effect is the reaction cross-section for ^{3}He and ^{10}B that has a negative coefficient of $-0.15 \%/_{^\circ C}$ that is five times larger than the measured coefficient of $0.03 \%/_{^\circ C}$. Thus, the positive coefficients for the electronics are required to help compensate for the cross-section effect.[17]

Long-term Stability

The issue of detector stability over time follows the same rationale as detector temperature stability. Neutron coincidence based assay systems achieve a measurement precision of better than 1 percent. As with any parameter that affects measurement uncertainty, the effects of system stability over time should be a small contribution. Although periodic recalibration of the system can mitigate a long-term shift in performance, a reasonable compromise is that the total efficiency variation over the application time of the detector should not vary more than 0.5 percent.

Safety

Any system deployed in a nuclear facility must meet stringent safety requirements both for the facility and personnel. Safety comprises several issues, some of which have been addressed in other items in this section. For example, high voltage is a safety issue and is addressed further on. Weight is a safety (and seismic) issue and will also be addressed separately. The remaining issues are materials and design. We cannot quantify design, other than to stipulate that the design of any replacement technology should not compromise safety in any way. The issue of material safety is best quantified using the standard Material Safety Data Sheet (MSDS) format and the National Fire Protection Association (NFPA) 704 labeling system. Under NFPA 704, the conditions for all materials for safety are:

> Health Level 1: Short exposure could cause irritation but only minor residual injury.
>
> Flammability (Level 1): Must be pre-heated before ignition can occur.
>
> Instability/Reactivity (Level 1): Normally stable, but may become unstable at elevated temperatures.
>
> Special Hazards: None

Uniformity of Spatial and Energy Response

The uniformity of spatial and energy response is largely dependent on the details of the neutron detector system design. These values can vary appreciably for ^{3}He systems, depending on system design. Spatial response uniformity is typically attained by attaching strips of neutron absorbers (e.g., cadmium) within the assembly to tailor the detector response. The absorber material is varied in length and thickness as needed to flatten the efficiency profile across the length and width of the detector. As it is difficult to quantify, it should be possible to design replacement technology systems with equal uniformity of spatial and energy response as is presently possible with ^{3}He detector systems.

Hazardous Content (for disposal)

The hazardous content for disposal requirement follows directly the provisions already established in the safety section for hazardous materials. The relevant MSDS data sheets should be used to establish means for disposal. All materials should be disposable by conventional means.

Relative Price

Relative price is fully included in the figure of merit calculation and is included here for completeness. For a comparable intrinsic efficiency and die away time, the relative price of a replacement technology system should be no more than a factor of two higher than the comparable ^{3}He system. Presently, the cost of the actual detector modules is the predominant cost for coincidence assay systems; therefore, a cost increase for a replacement technology will impact the cost of deployed systems proportionately.

Availability of Production Quantities

Availability of production quantities follows as a natural corollary to the commercially available requirement above. A presumptive replacement technology cannot be a laboratory demonstration; it must be a product that is in full serial production so that it can be used in system design and construction and installed in nuclear facilities in quantities matching the present usage of ^{3}He detectors.

Maintenance Requirements

Maintenance intervals should be in excess of four years, so as to not place an unnecessary technical burden on agency staff. Systems designed with replacement technologies should be easily accessible and modular in design, minimizing the time necessary for maintenance activities. The implementation of new technologies should add no unique or difficult conditions for performing maintenance on these systems.

High Voltage Limitations

Limiting the required high voltage for operation is both a safety concern and an engineering concern. The engineering issue is handling the high voltage so that there are no arcs, as these could damage the system. The safety concern is the high voltage hazard. Present ^{3}He systems operate at less than 2 kV. Gamma ray systems, which are used in the same environment, operated at nominally 3.5 kV. Therefore, a reasonable limit for the high voltage is 5 kV.

Size (footprint)

As discussed in the figure of merit calculation, the area of the neutron detector must include both the active and inactive areas, in order for a comparison to be valid. This aspect of size is already accounted in the figure of merit analysis. The remaining detector dimension is the thickness of the detector. Thickness is important because thicker ^{3}He detectors may be more efficient than thin ones because they may include more layers of ^{3}He tubes and moderators. Therefore, at equivalent detection efficiency, the detector thickness of replacement technology should be no more than twice the thickness of a comparable ^{3}He detector.

System Weight

The system weight is more appropriately defined as the system specific weight, or the weight divided by the volume of the detector. The purpose for considering system weight is primarily for reasons of safety: the detectors are installed in nuclear facilities and the greater the weight, the more difficult and hazardous the installation. Moreover, nuclear facilities have rigorous seismic requirements and the greater weight has an impact on seismic stability. An acceptable specific gravity would be twice the mass per volume of an equivalent ^{3}He detector.

Promising Detection Technologies Addressing IAEA Needs

Overview

The workshop was attended by a broad array of recognized experts in the field of neutron detection covering the most active areas of development, as well as a few new and novel technologies that have significant potential. As the primary objective of the workshop was to identify near-term replacement technologies, priority was given to replacement technologies that might have the ability to act as direct replacements for ^{3}He tubes in form and function. The intent was to minimize or eliminate an extensive redesign of the large installed base of instrumentation already deployed in the field. A few alternate technologies that departed from this physical constraint were also discussed, as they presented significant near- and long-term replacement strategies.

For both existing system retrofit and new system design and deployments, the implementation of a technology that emulates the operation and performance of ^{3}He, as defined in the requirements section, would provide the significant benefit of a transparent transition for both maintenance and user perspectives. Priority consideration was given to a replacement technology's ability to interface to the existing electronics and data acquisition and analysis infrastructure. As these detectors are primarily concerned with safeguarding nuclear material, this concept was particularly focused on compatibility with shift register-based coincidence and multiplicity neutron counting as related to the Point Model. One exception to this requirement is the operation of fast neutron detector technologies that require significantly higher speed data acquisition and signal processing.

Background

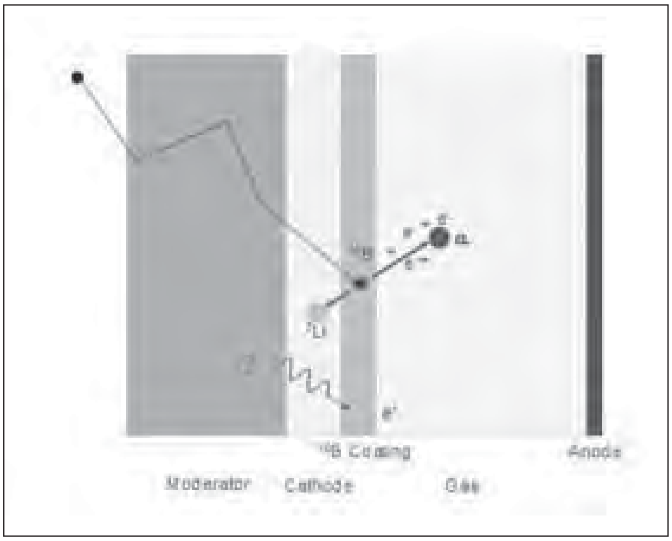
Some of the earliest gas-based thermal neutron detectors used boron triflouride (BF_3).[18] These detectors were later replaced with ^{3}He-based technologies due largely to the toxicity and hazardous nature of BF_3. The comparable performance, benign nature, and relative abundance of ^{3}He resulted in rapid market dominance and precluded significant research and development of alternative neutron detection technologies for most applications.

^{3}He is a byproduct of tritium decay, tritium being primarily produced in nuclear weapons programs. The general cessation of nuclear weapons development has created a situation in which the production of tritium and resulting supply of ^{3}He is not only insufficient to meet current needs, but is also decreasing with time. The result has been a renewed, aggressive interest in alternative ^{3}He detector technology. In many cases, these activities are focused on variations in, or optimization of, materials and configurations that have been previously identified, but not fully developed. New approaches are also being pursued through the development of new materials. Novel chemical compounds and advances in materials science have broadened and accelerated these developments. Additionally, significant advances in real-time signal and data processing have provided the enabling technology to realize the capabilities of earlier detector systems and concepts previously relegated to laboratory environments due to overall system complexity.

Technologies

As this workshop did not provide sufficient time to perform a comprehensive review of all technologies with neutron detection potential, a number of leading candidates were presented by workshop attendees and subsequently evaluated for suitability by the technology sub-group. The technologies of interest that appeared to be most promising were liquid scintillator and boron- or lithium-based materials and systems. ^{3}He detector performance, as articulated in the requirements section, was used as the baseline comparison from which many conclusions were drawn. The maturity of these alternate detector technologies varies from well-established and commercially available (e.g., liquid scintillators, ^{10}B) to those still in the research and development phase (e.g., CLYC, novel plastic scintillators). With respect to the

Figure 6. ^{10}B-lined tube cross-section showing a thermal neutron interaction[19]



^{3}He baseline, each technology provides both advantages and disadvantages, and all alternative technologies include considerable compromises. Those specific technologies that exhibit potential as candidate replacement technologies that were also presented at the workshop are discussed below.

^{10}B-based Detectors

The majority of the alternative neutron detector technologies being pursued are based on the use of ^{10}B in a variety of design implementations. Designs include boron-doped compounds and liquids and boron-lined plates and gas-filled tubes. ^{10}B is an attractive material due to its moderately high thermal neutron (0.025 eV) cross-section [the ^{10}B cross-section (3840 Barns) is approximately 72 percent of ^{3}He (5330 Barns)] and compatibility with existing signal processing electronics and data acquisition systems.

While it may appear that ^{10}B gas-filled tube technologies could provide the much desired near-term solution, a number of issues need to be considered or remain to be resolved before this technology can be considered for implementation. The primary obstacle to deploying ^{10}B gas detectors is relatively low detection efficiency as compared to ^{3}He. Lower efficiency results in the need for higher numbers of tubes for a given application and a corresponding larger detector system. New developments in detector technology based on small diameter tubes or parallel plates provide improved performance relative to comparable ^{3}He-based detectors. However, the performance of these technologies needs to be evaluated in the full safeguards counter configuration.

A secondary issue is gamma sensitivity of ^{10}B-doped liquid scintillators, though this has been minimized through the application of advanced pulse shape discrimination (PSD) techniques.

^{10}B-lined proportional detectors are tubes or plates that have a very thin coating of ^{10}B-doped material, on the inner surface of the tube (Figure 6). The active material layer has been optimized to minimize recombination of the alpha particle (mean free path ~3.6μm) and Li recoil nucleus (mean free path ~1.6μm) reaction products before interacting with the gas. The very short mean free path indicates the need for a very thin layer of material, directly affecting detection efficiency. Many creative detector designs have been developed specifically to address this issue. Moderately complex structures comprised of multiple small diameter tube assemblies have been fabricated to increase the interaction area, thereby increasing detection efficiency. A recent example of a multiple tube assembly that exceeds 40 percent that of a comparably-sized ^{3}He detector has been reported by Tsorbatzoglou and McKeag.[20]

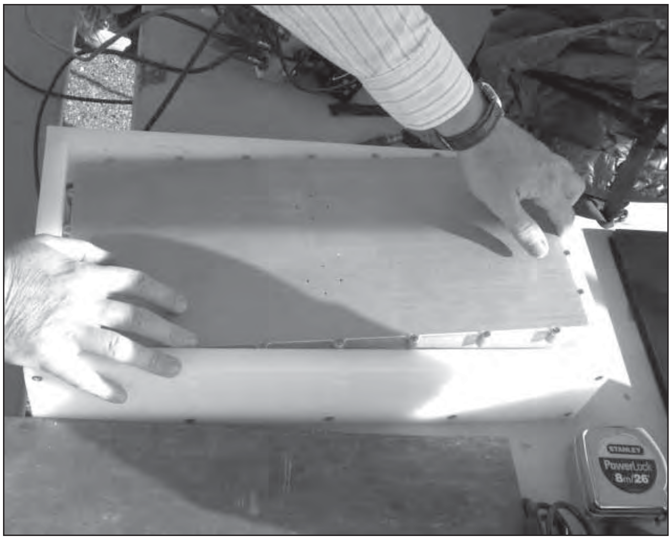
Doped liquid scintillator compounds contain a small percentage of ^{10}B in the active detection material (up to ~5 percent). Most liquid scintillator fluids are sensitive to both fast neutrons and gamma and with the addition of ^{10}B, can also be made sensitive to slow neutrons. Each response signal can be separated with advanced PSD techniques, though insufficient rejection of gamma rays results in false neutron counts. Higher ^{10}B doping percentages have been attempted to increase detector efficiency, but a corresponding reduction in light yield results, offsetting any potential benefit. Advances are being made in refining the chemistry and PSD techniques,[21] though this technology is not sufficiently advanced to enable consideration for near-term applications.

^{6}Li-Based Detectors

^{6}Li-based scintillating detectors are primarily comprised of liquids and solids, as a stable, lithium-containing proportional gas does not exist.[22] The detection mechanism of ^{6}Li is similar to ^{10}B, though it has a higher Q value (4.78MeV vs. 2.31MeV, respectively), as well as an alpha particle and triton rather than an alpha particle and Li recoil nucleus. Together, these features provide longer mean free paths that allow a greater layer thickness before recombination affects the detection efficiency (26μm vs. ~3.6μm, respectively). The converter material can therefore be an order of magnitude thicker for ^{6}Li than for ^{10}B, providing a greater atomic density per area and the potential for higher efficiency. Unfortunately, this is offset by the reduced ^{6}Li neutron cross-section (940 Barns)—about 25 percent that of ^{10}B, as well as about 18 percent that of ^{3}He—resulting in a similar detection efficiency to ^{10}B for a given geometry. ^{6}Li-based detectors are produced in three primary forms: Li-coated non-scintillating fibers (or paddles) and Li-loaded glass fibers.

Li-Coated Scintillating Fibers are complex, multi-layered structures designed with alternating layers of lithium fluoride/zinc sulfide compounds (^{6}LiF/ZnS(Ag)) with wavelength shifting fibers or flat light guide layers designed to extract the scintillation light to photomultiplier tubes. Detection efficiency increases with the number of layers. It should be noted that these layered designs are typically flat and are therefore directionally sensitive. The ZnS component adds gamma ray sensitivity, but the combination of the typically thin layer (less than 1mm) and the implementation

Figure 7. ^{6}Li-loaded glass fiber neutron detector and associated high-density polyethylene (HDPE) moderator enclosure



of PSD techniques significantly reduce gamma interference. An example of this technology is shown in Fig 7. The system is commercially available and configured in a form factor that is similar to a ^{3}He slab geometry detector. An issue that may limit potential applications is the directional sensitivity characteristic of the detector. This system was designed specifically to address portal monitor applications for homeland security and was tested extensively at Pacific Northwest National Laboratory (PNNL).[23]

Li-loaded glass fibers use cerium (Ce) doping to produce scintillation light and have similar characteristics to the layered detector structures noted above. The efficiency is somewhat lower for a given geometry and the PSD for gamma rejection does not perform as well as for LiF/ZnS-layered detectors. Detectors fabricated with Li-loaded glass fibers can be produced with geometries that are not directionally sensitive and possibly in a form factor similar to a ^{3}He tube. An example of a commercially available detector is shown in Figure 7. This detector is comprised of a number of glass bundles surrounded by an HDPE moderator. This detector was also tested extensively by PNNL for Homeland Security applications.[24]

Liquid Scintillators

Organic liquid scintillators have been implemented in nuclear and high-energy physics applications for decades. There were a number of limiting factors that have historically precluded their implementation in safeguards applications. From a safety perspective, the common liquids used for neutron detection were hazardous and poisonous chemical compounds that also featured a low flash point, presenting a fire or explosion hazard. These characteristics alone eliminated the possible consideration of the technology in nuclear facilities. In addition, extensively complex data acquisition hardware and off-line data analysis was required.

The recent introduction of high flash-point, non-hazardous liquid scintillators with comparable performance have significantly reduced the safety concerns. Additionally, dramatic advancements in electronics and embedded, real-time processing capabilities have provided the final enabling technology to allow for the consideration of liquid scintillators in safeguards applications, though requiring possible modification of existing data acquisition infrastructure. This technology was demonstrated at the workshop.[25]

The performance of liquid scintillators is very promising. One of the primary benefits of detecting fast neutrons is realized in coincidence measurement applications. The time allowed for coincident neutron detection is less than 100ns, a period that is roughly three orders of magnitude less than a typical thermal neutron detector. This smaller detection window results in a dramatically reduced accidental coincidence count rate. In addition, intrinsic efficiency is reasonable at ~22 percent for a 12.7cm diameter x 7.6 cm thick detector (Figure 8).

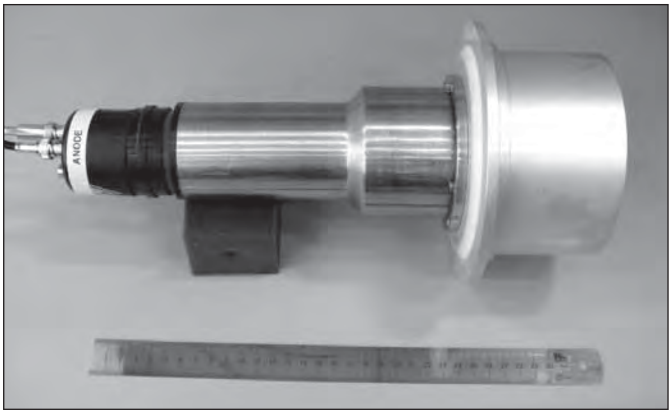
There are a number of outstanding issues that remain to be resolved before liquid scintillators can be considered suitable for safeguards applications. The following list articulates significant performance metrics that require characterization.

Gamma Ray Rejection—There are a number of PSD algorithms in use that analyze detector pulses for characteristics that would indicate either a gamma ray or neutron interaction. While these algorithms perform well, they are not perfect and detector signal pulse shapes can vary sufficiently from pulse pile-up or optical distortion to allow the PSD algorithm to misinterpret the pulse. The main concern is gamma ray detections that appear as neutrons (false neutrons). This performance parameter is referred to as Gamma Absolute Rejection Ratio for Neutrons (GARRn) in homeland security applications and is primarily associated with the performance of ^{3}He-based detectors. The significance of this metric with respect to safeguards applications will need to be determined, particularly for detectors that provide both neutron and gamma ray detection capabilities.

Neutron/Gamma Coincidence Effects—While liquid scintillators have the benefit of a very fast response, on the order of a few nanoseconds, this fast detection response of fast neutrons may also result in the loss of neutron events due to coincident gamma ray detection. Since the detector can respond to only one event at a time (discounting pulse pileup events), an exceptionally high gamma ray field may increase the dead-time of the detector sufficiently to interfere with the detection of neutrons. The existence of this effect is being determined and if proven significant, mitigation strategies (e.g., shielding, detector geometry, using a larger number of smaller detectors) will need to be developed.

Thermal Stability—As noted in the Operational Requirements section, detector technologies should exhibit reasonably stable performance over a representative environment and for an extended period of time. The particular specifications vary with each application and suitable technologies are selected. Liq-

Figure 8. Liquid scintillator neutron detector using EJ309 high flash-point scintillation fluid



uid scintillators are being evaluated for limitations with respect to these characteristics prior to being considered for authorized use and initial experimental data indicates that the temperature stability of the detector and photomultiplier tube assembly is reasonably stable within the anticipated temperature range (10°C - 45°C).

Plastic Scintillators

The development of a new family of plastic scintillators was briefly described by representatives from Lawrence Livermore National Laboratory (LLNL).[26] Initial reported performance assessments indicated that the neutron and gamma ray sensitivity and separation (required for PSD) are similar to liquid scintillators. All of the standard concerns with respect to production, material uniformity and quality, environmental effects, temperature effects, and long-term stability and performance of a new material are present and are to be addressed as components of the development program. This technology is very new, progressing rapidly, and if successful has the potential to address a large number of detector applications.

Miscellaneous Detector Technologies

The following detector technologies were presented and, while they represent significant advances in capabilities or research and development of novel neutron detector technology, their maturity is insufficient to allow for consideration in the development of safeguards systems for the foreseeable future.

BF_3 Detectors—This detector was discussed at the workshop, but it was understood that this technology, while presenting a reasonable replacement for ^{3}He from performance and form factor perspectives, is unacceptable due to the well-known hazardous nature of the gas. Even though manufacturers indicate that the risk of mechanical failure that would lead to a gas leak is extremely remote and insignificant, occurrences of such failures have been documented. The risk is unacceptable at any level, and unfortunately precludes the use of BF_3 in IAEA systems.

CLYC Detectors, a new family of detector crystals developed by Radiation Monitoring Devices, Inc. (RMD), is produced in three chemical forms (Cs_2LiYCl_6, $Cs_2LiLaCl_6$, and $Cs_2LiLaBr_6$) to enhance different characteristics of the material for different applications. From a neutron detector and PSD perspective, Cs_2LiYCl_6 appears to be most promising. The Li component in the material provides the neutron detection sensitivity in an otherwise purely gamma ray sensitive device. From the gamma ray detection perspective, the material performs better than NaI(Tl) and approaches that of CeBr (~4 percent FWHM at 662keV). Initial data for one of the alternate forms ($Cs_2LiLaBr_6$) exceeds that of LaBr (~2.9 percent FWHM at 662keV), though neutron detection PSD is relatively poor. The crystal volumes currently produced are on the order of a few centimeters on a side, though larger volumes are being pursued. All of the same performance, reliability, stability, and lifetime characteristics will need to be assessed. This technology shows great promise for future applications that do not require large area neutron detectors.

Silicon-Based Detector technologies are being pursued by a number of organizations. Recent progress in detection efficiency and gamma ray rejection has been reported from a collaborative project between LLNL and the University of Nebraska.[27] These detectors are created by growing dense pillar structures of silicon and filling the voids with ^{10}B. The silicon component makes these detectors gamma ray sensitive, though the combination of small detector volume and the low Z of silicon minimize gamma ray interactions and the resulting interference. The development is continuing and could be considered for future applications that require high efficiency in a small volume or geometry neutron detector.

Conclusion

Many exciting developments have taken place in a relatively short period of time. A broad array of technologies have been pursued and each address different and in some cases overlapping segments of the field. Even with the diverse set of activities in pursuit of the performance and capabilities of ^{3}He, none of the detector technologies that are readily available or nearly commercially available can satisfy the fundamental replacement technology requirements as stated in the requirements section of this document in a like-for-like, direct replacement methodology.

The closest match to all aspects of the ^{3}He baseline is BF_3, which is not an option for the reasons stated above. The next best fit to the requirements is the family of ^{10}B-based detector technologies. Recent advances in ^{10}B-lined gas counter detector designs make these technologies more suitable for near-term replacement. Additional infrastructure changes will also need to be considered for ^{10}B-doped liquid scintillator systems. The performance of full size safeguards systems needs to be evaluated, though significant geometry and moderate infrastructure changes will need to be considered that will preclude their use in the very near-term applications. For those applications with an immediate need, ^{10}B detectors may be a reasonable candidate. The same can be said for the ^{6}Li-based detector technologies, though lower efficiency, directional sensitivity, and poor gamma ray rejection reduce possible implementations. New configurations and novel detector fabrication methodologies may address these issues as the technologies mature.

Liquid scintillators are being developed by a number of groups and are quickly advancing. While gamma ray rejection is not very high, the detection of fast neutrons rather than thermal neutrons and the exceptionally fast data acquisition may reduce the significance of this performance category. Liquid scintillators cannot be considered for near-term replacement of ^{3}He due to extensive geometry and infrastructure changes necessary for implementation. This technology is better considered for next generation system development. In addition, the promise of new plastic neutron detector technology would use the same signal processing and data acquisition hardware. Advances in plastic neutron detectors should be monitored and regularly evaluated against the application requirements.

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Further Intrusion or Different Political Priorities? What are the Main Reasons Behind Countries' Non-Signature of the IAEA Additional Protocol?

Sara Z. Kutchesfahani
Los Alamos National Laboratory. Los Alamos, New Mexico USA

Abstract

The Additional Protocol (AP) was agreed upon by the International Atomic Energy Agency (IAEA) Board of Governors in 1997 after the discovery of Iraq's clandestine attempted nuclear weapons program—and other nuclear proliferation events in the early 1990s—as a way to strengthen and provide more efficient safeguards, extending the classical safeguards system. It provides better tools to carry out inspections on a more routine basis because it allows the IAEA to collect information on a country's nuclear activities, visit declared sites, and make unannounced visits to declared sites. Currently, 140 countries have signed the AP. However, a number of countries with significant nuclear-related activities have not yet signed the AP. This paper assesses the motivations behind these countries' reluctance toward signing the AP, questioning whether it is because of the burden of safeguards and further intrusion, or whether it is because of different political priorities. The paper suggests that it is important to understand the reasons behind why some countries will not sign the AP so that these reservations can, in time, be overcome.

Introduction

After major failures in nuclear safeguards were discovered in Iraq following the 1991 Gulf War, Hans Blix, then director general of the International Atomic Energy Agency (IAEA), requested recommendations on strengthened and more efficient safeguards in order to extend the classical safeguards system and to increase the IAEA's investigation rights. Iraq's clandestine nuclear weapons program exposed the limitations of the existing safeguards system, encapsulated through INFCIRC/153, which focused exclusively on declared nuclear material and facilities, leading Jeffrey Lewis, a respected nonproliferation analyst at the James Martin Center for Nonproliferation Studies, to claim, "the existing safeguards regime is inherently vulnerable to the insistence that the 'absence of evidence is not evidence of absence.'"[1]

Further events in the early 1990s influenced the thinking behind the formation of the Additional Protocol (AP). These included the dissolution of the Soviet Union, South Africa's nuclear rollback, and the nuclear activities unfolding in the Democratic People's Republic of Korea (DPRK). First, the dissolution of the Soviet Union resulted in the overnight creation of four nuclear weapon states, including Russia, Belarus, Kazakhstan, and Ukraine. Second, South Africa's decision to voluntarily rollback its nuclear weapons program and its subsequent collaboration with the IAEA helped the agency understand the level of cooperation required between itself and the state to effectively address the completeness of states' nuclear material declarations. Finally, the ad hoc/special inspections in the DPRK provided the agency with the opportunity to use environmental sampling as a new technical safeguards measure. In addition, these inspections illustrated the importance of the agency being able to receive and use third-party information. As a result of these events, by 1997, the voluntary Model Additional Protocol—INFCIRC/540—was agreed to by the IAEA's Board of Governors. It is important to note that INFCIRC/540 was thus labeled the AP because it supplements states' existing safeguards agreements with the IAEA.[2]

Having briefly outlined the *raison d être* for the creation of the AP, this paper first introduces how the AP serves as a mechanism to strengthening of international safeguards. Second, it assesses the current status of the AP, outlining how many states have an AP in force. Third, it presents a brief overview highlighting the reasons for not signing an AP offered by some countries with significant nuclear activities. The premise of this paper is to try to understand the reasons behind countries' reluctance to sign an AP so that such reservations can be overcome, which is where the paper concludes.

How Does the AP Strengthen International Safeguards?

The existing safeguards literature provides many compelling reasons for how and why the AP strengthens international safeguards.[3] Before his retirement as the director general of the IAEA, Mohamed ElBaradei said, "Without the AP, the IAEA has no capability to verify undeclared facilities."[4] This is because, in short, the AP allows the IAEA to collect information on a country's nuclear activities, visit declared sites, and make unannounced visits to declared sites. In extraordinary circumstances, the IAEA can ask for access to undeclared or non-nuclear sites. Furthermore, according to John Carlson (former director general of the Australian Safeguards and Nonproliferation Office):

> The AP substantially strengthens levels of assurance on the peaceful nature of nuclear activities in countries that have 'comprehensive' safeguards agreements, by broadening the information to be reported to the IAEA and the access given to inspectors. Without these extra measures, the IAEA's ability to detect undeclared nuclear activities is substantially reduced.[5]

These "extra measures" led Theodore Hirsch to argue in a 2004 *Nonproliferation Review* paper that the AP is "an effort to transform IAEA inspectors from accountants to detectives."[6] The extra measures include the following:

- Provision of information: The AP provides additional information and verification on nuclear and nuclear-related activities (INFCIRC/540 Articles 2-3).
- Complementary access: The AP provides better tools to carry out activities to investigate inconsistencies and completeness in the IAEA's knowledge about a state's nuclear fuel cycle and research activities in a less confrontational manner (compared with special inspections); inspectors will have greater access rights at any suspect location and at short notice; inspectors can use environmental sampling and remote monitoring techniques to detect illicit activities (INFCIRC/540 Articles 4-10).
- Automatic visa renewal for inspectors "to cover the duration of the inspector's designation" (INFCIRC/540 Article 12).
- Permission and protection of free communication from inspectors with the agency (INFCIRC/540 Article 14).
- Protection of confidential information: The IAEA will "maintain a stringent regime to ensure effective protection against disclosure of commercial, technological, and industrial secrets and other confidential information coming to its knowledge" (INFCIRC/540 Article 15).

What is the Current Status of the AP?

Currently, more than 63 percent of states that have a safeguards agreement with the IAEA—not necessarily IAEA member states alone—have an AP in force. While there are 154 IAEA member states, the IAEA has safeguards agreements in force with 178 states in total. According to the IAEA website, as of July 24, 2012, of the 178 states with a safeguards agreement, there are 142 that have at least started negotiations of an AP with the IAEA Board of Governors, and of those, 117 have an AP in force.[7]

However, while the majority of states that have a safeguards agreement with the IAEA also have an AP in force, there are a number of states that do not have an AP in force. States that do not have an AP in force fall into three areas. These are countries that (1) have not begun negotiations of an AP with the IAEA Board of Governors (e.g., Argentina, Belize, Bolivia, Brazil, Cambodia, Egypt, Ethiopia, Israel, Lebanon, Nepal, Oman, Pakistan, Qatar, Saudi Arabia, Sierra Leone, Sri Lanka, Sudan, Syria, Tonga, Venezuela, Yemen, and Zimbabwe), (2) have not signed an AP even after it was approved by the IAEA Board of Governors (e.g., Algeria, Guinea-Bissau, Republic of Moldova, and Vanuatu[8]), and (3) do not have their signed AP entered into force (e.g., Andorra, Belarus, Benin, Bosnia and Herzegovina, Cameroon, Cape Verde, Côte d'Ivoire, Djibouti, Guinea, Honduras, India, Iran, Iraq, Kiribati, Liechtenstein, Malaysia, Senegal, Serbia, Thailand, Timor-Leste, Tunisia, Vietnam, Zambia). In these three categories, the countries are predominately composed of the regions of the Middle East/North Africa, South America, and Asia.

In this paper, the analysis focuses on select countries from these regions with noteworthy nuclear activities. While it is open to question (not to mention beyond the scope of this paper) whether this select sample is in any way representative of the entire sample of non-AP signatories, it is important to note that these countries are singled out primarily because of recent media attention directed toward their significant nuclear activities. According to Carlson, "significant nuclear activities" translates as "any amount of nuclear material in a facility or 'location outside facilities', or nuclear material in excess of the exemption limits specified in paragraph 37 of INFCIRC/153."[9] In other words, these are countries where having an AP in place would assure the IAEA and the international community that their significant nuclear activities were indeed of a peaceful nature.

Why Won't These States Sign an AP?

It is important to reflect on the research methodology undertaken for this research before offering a brief overview of the different reasons for these countries' non-signatures. Since the main premise of this research was to understand the official reasons *why* these countries would not sign an AP, official statements, where possible, were consulted. In other words, statements emanating from official/government representatives from the respective countries were accessed and analyzed, rather than op-eds in newspapers and/or journals from eminent scholars and analysts. It should be noted, however, that official statements do not always provide the full, true, and complete statements of the actual reasons. Yet, they are a first step in providing a meaningful assessment, which is currently lacking from the existing literature, and as such, is the focus of this paper. It is important to understand the reasons behind these countries' reluctance in signing an AP so that these reservations can, in time, be overcome. Furthermore, the underlying question posed with respect to the different reasons is whether these countries' reluctance to sign an AP is because of the burden of safeguards and further intrusion, or because of different political priorities. It is important to note that the term "different political priorities" refers to pressing internal political matters of concern. For example, ensuring the security and survival of a ruling regime would take priority over pursuing further nuclear safeguards.

Algeria, Egypt, Iran, and Syria: Less Safeguards Specific, More Political Priorities Centric

The following statements drawn from Algeria, Egypt, Iran, and Syria indicate that there is not one dominant factor preventing these countries from signing an AP. However, with recent events unfolding in the region, specifically the Arab Spring, it can be argued that the reluctance in signing an AP has more to do with political priorities, and less to do with further inspections.[10] It is clear that the priorities for these countries concern regime survival and security rather than strengthening their existing safeguards agreements.

Algeria

In 2004, Algeria had a draft AP approved by the IAEA Board of Governors. Based on the following statements from Algerian officials, it would appear that while the underlying reasons cannot be clarified, Algeria is stalling its decision to sign an AP. For example, in 2005, Noureddine Bendjaballah, Commissioner for Algeria's Atomic Energy Commission said, "Major work is under way toward the signing [of an AP]. We are in the preparatory phase. We have instructions to move very quickly, but I can't give a timetable."[11] Four years later, Chakib Khelil, Minister of Energy and Mines, said, "The Algerian government will consider, before the end of this year, the bill to be ready at the beginning of next year," but as of the time of this writing, it has yet to sign it.[12]

Egypt

Of all the countries in the region, Egypt has been the most vocal in its opposition to the AP. It has yet to negotiate an AP with the IAEA and it has publicly declared that it has no intention of doing so. In fact, in most official Egyptian statements, the issue of Israel is repeatedly mentioned. For example, in December 2007, Egyptian Deputy Foreign Minister Ramzy Ezzedine Ramzy said, "Egypt will not sign the AP, since it is a voluntary thing. In comparison with Israel, which chooses to stay outside international legitimacy and not join the NPT, Egypt will not accept any additional commitment."[13] In a more recent statement, the Egyptian Permanent Representative to the United Nations, Ambassador Maged Abdelaziz, re-emphasized that the Egyptian reluctance to signing an AP was in part due to the Israel issue. In his speech to the 2010 NPT Review Conference, he said,

> Israel's unsafeguarded nuclear facilities and activities […] continue to have a destabilizing impact on regional peace and security, as well as undermining international nonproliferation efforts. […] Despite this, Egypt remains firmly committed to honoring its obligations under its comprehensive safeguards agreement, and has remained so consistently ever since entering into those obligations. Therefore, we are extremely surprised when we are asked to enter into additional verification obligations, especially in light of the continued existence of completely unsafeguarded facilities in the Middle East.[14]

Iran

Of the four countries analyzed in this region, Iran is the only country to sign an AP with the IAEA. It signed in 2003 and began applying it on a provisional basis, but then suspended it in 2005. Since then, it would appear that Iran does not have any interest in entering it into force. According to Ambassador Ali Asghar Soltanieh, Iran's Permanent Representative to the IAEA, "Iran's strategy is based on not accepting the AP as long as Iran's nuclear dossier remains at the UN Security Council (UNSC)."[15] This statement would suggest that, according to the Iranians, the UNSC—rather than Iran itself—is somehow responsible for Iran not complying with the AP. Iran can eliminate the UNSC interest immediately by complying with UNSC resolutions and providing the information required by the IAEA to make a determination that Iran is in compliance. Iran's refusal to provide such non-proprietary nor sensitive information is what keeps it in front of the UNSC, which Iran says is preventing it from entering the AP into force.

Syria

Similar to Algeria, the statements emanating from Syria vis-à-vis the AP do not offer a clear understanding into the real reason behind its reluctance in signing the AP. For example, in January 2011, President Assad declared, "We are not going to sign the AP. We can only follow the NPT that we are signatory to, and we do not have any problem with this."[16] This statement implies that Syria is not going to sign the AP. Syria has not begun negotiations of an AP with the IAEA, and based on this statement from President Assad, it is quite clear that it has no intention of doing so in the immediate future. The regional turmoil, not to mention the domestic uprising facing Assad's regime, might perhaps be more of a priority for Assad, than strengthening safeguards.

Argentina, Brazil, Venezuela: The AP is Voluntary; Let's See Some Progress on Disarmament First

Argentina, Brazil, and Venezuela offer different reasons for their reluctance to sign the AP. Yet, based on their statements, similar to the countries analyzed above, it is clear that not one dominant factor is preventing these countries from signing an AP. However, what all three countries have in common regarding the AP is that none of them have begun negotiations of an AP with the IAEA.

Argentina

Interestingly, it was quite difficult to come across an official Argentine statement in relation to the AP. However, some analysts have speculated that Argentina's non-commitment to the AP may in part have something to do with Brazil's reluctance to sign it (given the two countries' historic former rivalry in the nuclear sphere) and that the AP itself is of a voluntary nature.[17] It is important to note that Argentina and Brazil's attitudes toward the nuclear nonproliferation regime, including the Nuclear Nonproliferation Treaty (NPT) and the Treaty of Tlatelolco, which established the Latin American Nuclear Weapon Free Zone (an area that is protected against the use, storage, and testing of nuclear weapons), have historically been the same. For example, in the 1970s, both states deemed the NPT as discriminatory. Upon the creation of the Brazilian-Argentine Agency for Accounting and Control of Nuclear Materials (ABACC) however in 1991, both countries became integrated within the international nuclear nonproliferation regime, with Argentina taking the lead in signing agreements first. For example, it was the first to sign the NPT and did so in 1995, with Brazil following two years later, in 1997. In addition, Argentina was the first to join the Nuclear Suppliers Group in 1994, with Brazil following two years later, in 1996. Perhaps the tables have now turned with Argentina waiting for Brazil to sign the AP first before it does. Either way, whatever Argentina or Brazil decides on the AP, it is safe to assume, that based on their past nuclear behavior, the action will be mirrored.

Brazil

Brazil is the most outspoken in its refusal to sign the AP, not only in the region, but among the other non-signatories to the AP. Its reluctance is based on two reasons: (1) the lack of progress in disarmament seen by the nuclear weapon states, and (2) the fact that further inspections are deemed too intrusive.

Brazil's national defense strategy, released in 2008, states that Brazil will not move forward with the AP until and unless the nuclear weapon states make progress on disarmament. It states, "Brazil will not adhere to amendments to the NPT extending the restrictions of the Treaty, until the nuclear weapon states advance in the central premise of the Treaty: their own nuclear disarmament."[18]

The issue of disarmament is repeatedly referred to by different Brazilian officials who comment on the AP. For example, at the 2011 Carnegie International Nuclear Policy Conference, Ambassador Celso Amorim, former Minister of External Relations and now current Minister of Defense, said, "I honestly don't see how Brazil will take further steps in relation to nonproliferation before seeing some steps being taken on disarmament."[19] Furthermore, the lack of progress in disarmament fuels Brazilian suspicion that the obligations of NPT signatories are biased in favor of NPT nuclear-weapon states. For example, the Brazilian Permanent Representative to the Conference on Disarmament, Ambassador Luiz Filipe de Macedo Soares, in his statement to the 2009 NPT Preparatory Committee explained, "The difficulties and challenges facing the international community in the implementation of the NPT […] derive from the unbalance in the implementation of all its obligations by the different actors." [20]

A further reason that Brazil will not sign the AP is because it deems the further inspections warranted by an AP as too intrusive. Brazil does not want to open up the nuclear installations in its universities for reasons of independence, autonomy which has a long tradition in Brazil especially insofar as the nuclear realm is concerned and academic freedom. Odair Dias Gonçalves, president of Brazil's National Nuclear Energy Commission (CNEN) explained, "The AP requires many new inspections. The universities are subject to safeguards and inspections. Universities in Brazil are proud and jealous of their independence, autonomy, and academic freedom."[21]

Venezuela

Like Argentina, Venezuela has not pronounced an official reason for its non-signature to an AP. However, President Hugo Chavez has publicly stated that Venezuela is, "taking on the project of nuclear energy for peaceful purposes, and they aren't going to stop us."[22] Based on this statement, it would appear that Venezuela has not signed an AP simply because it does not want to.

Politics Rules

The focus here is on Burma alone, given that it is the only NPT signatory and the only country with widely suspected nuclear-related activities in the region without an AP signature. It should be noted that the DPRK has withdrawn its enforcement of their NPT agreement. However, with the recent death of Kim Jong-il, there is strong urging from countries in the region and the United States for the new ruler of the DPRK to again recognize their commitments (possibly referring to the NPT), which would be the first step in bringing an AP into force.[23]

Burma (Myanmar)

In a statement to the IAEA's 54th General Conference, 2010, Ambassador U Tin Win, the leader of the Myanmar Delegation explained, "While supporting the nonproliferation of nuclear weapons, Myanmar has also all along supported the legitimate rights of every state to the use of nuclear energy for peaceful purposes. Myanmar believes in the principles of *non-politicizing* the NPT and non-discrimination against developing countries in the NPT implementation."[24]

What Do These Reasons Tell Us and How Can These Reservations Be Overcome?

Based on the above countries' rationale for not signing the AP, it is clear that their reluctance has more to do with different political priorities and less to do with the notion of further intrusion an AP would entail. However, some of the countries analyzed in this study have openly declared that they have no desire to sign an AP.

In order to overcome such reservations, an outreach program is to be encouraged, answering the following two questions.[25] Over time, this may increase the likelihood that these countries sign and enter into force an AP.

What are the Advantages of the AP, and for whom?

It would be important to outline the advantages of the AP, as well as for whom it would be advantageous. Skeptics may argue that there is a trust issue: if we trust the countries with an existing IAEA agreement, why would we need to further inspect them through an AP? It needs to be made clear that the advantages of the AP would include a strengthened international safeguards system and an effective verification mechanism ensuring all nuclear-related activities are for peaceful purposes only, and are in the interest of international security. Furthermore, it is advantageous to the state given that the AP has more of a consultative nature with communications going between the IAEA and the state versus the more intrusive and blunt nature of special inspections.

How Does the AP (INFCIRC/540) Differ from INFCIRC/153?

It would be important to highlight to what extent the AP supplements and complements—and does not replace—INFCIRC/153 and, in particular, what it covers that INFCIRC/153 does not cover, at least from the perspective of countries that have yet to sign an AP.[26] For example, it needs to be made clear from the outset that INFCIRC/153 focuses on nuclear materials, while INFCIRC/540 focuses on some aspects of nuclear research, but its largest focus is additional and earlier reporting of activities directly related to the nuclear fuel cycle and nuclear materials, along with mechanisms to verify these declarations. It should be noted that the AP includes declarations of some nuclear research, as well as some nuclear materials, for example, heavy water and nuclear-grade graphite.

Furthermore, and perhaps more importantly, it needs to be made clear that under INFCIRC/153, states can be subjected to special inspections. Special inspections allow the IAEA greater access to information and to locations. However, they are more intrusive since they are used as a last resort after *all* inspection processes are exhausted. On the other hand, INFCIRC/540, invokes complementary access—a friendlier approach without deadlines and with a consultative process. In addition, INFCIRC/540 provides both additional information and verification. In short, it provides the IAEA with better tools to inspect on a more routine, regular basis.

However, it should be noted that while an outreach program can help to address the technical issues surrounding an AP, it may not have the desired effect, given that, based on the above analysis, the countries explored in this paper, especially those that comprise the Middle East/North African region, are reluctant to sign an AP based not on technical grounds, but on different political priorities, notably regime survival.

Conclusion

To conclude, this paper assessed the motivations behind countries with significant nuclear-related activities reluctance toward signing the AP. It can be argued that this reluctance has more to do with different political priorities and less to do with the notion of further intrusion an AP would entail. In other words, ensuring the survival and security of a ruling regime was, in most of these cases, prioritized over pursuing further safeguards. In the case of Brazil, however, it was made clear that until and unless the nuclear weapon states made open progress in disarmament, the Brazilian government would not begin negotiations of an AP with the IAEA Board of Governors. Essentially, this research indicated three main reasons why countries will not sign an AP: (1) additional IAEA intrusion, (2) political reasons, and (3) lack of disarmament. The author concludes that it is important to understand the reasons behind why these counties would not sign an AP so that, in time, these reservations can be overcome.

The views expressed in this paper are the author's own and not those of Los Alamos National Laboratory, the National Nuclear Security Administration, U.S. Department of Energy, the Institute of Nuclear Materials Management, or any other agency. (LA-UR 11-05028).

Since January 2011, Sara Z. Kutchesfahani has been a post-doctoral research associate in the Nuclear Engineering and Nonproliferation Division at Los Alamos National Laboratory. She completed her PhD in political science in November 2010 from University College London. Her book Politics & The Bomb: The Role of Experts in the Creation of Cooperative Nuclear Nonproliferation Agreements, *published by Routledge/Taylor & Francis, will be coming out in late 2013. Her work at LANL includes a number of nonproliferation policy projects including research in the IAEA's Additional Protocol, the role of special inspections, and contributing to the teaching in the Nonproliferation Division's Safeguards Policy and Technology Summer Workshop. In addition, since January 2012 she has been teaching an upper-level undergraduate/postgraduate political science course, "Nuclear Safeguards & Security Policy," at the New Mexico Institute of Mining and Technology. Previously, she worked at the International Institute for Strategic Studies (London) under the mentorship of Dr. Gary Samore, at the European Union Institute for Security Studies (Paris), at LANL (as a Nuclear Nonproliferation Science Fellow), and at the RAND Corporation (Washington, DC).*

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Taking the Long View in a Time of Great Uncertainty

Challenges and Opportunities Ahead

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

In previous columns, we have looked into the second decade of the new millennium and found that it is fraught with challenges, both for the world and the INMM. However, there are also opportunities for the Institute to contribute to solutions, as world leaders contend with the challenges of an uncertain future. These opportunities lie at the heart of the Institute's mission, supporting nuclear materials management and the nuclear professions, in all of their diverse and complex variations. One of the most important elements of the Institute's success over the past five decades, and an area that is critical for the future, is its role in helping to provide a venue for international collaboration for technical and policy issues.

As the leadership of the Institute addresses the challenges that lie ahead, it is important for us to revisit the legacy of the INMM, and its contributions to today's international environment, so that we can all serve as *ambassadors* of the Institute in our spheres of influence.

Five Decades of Contributions to the Nuclear Professions

The INMM has made more than five decades of contributions to the nuclear professions and global nuclear security, with historical ties in the United States going back to the Atomic Energy Commission (AEC), the Energy Research and Development Administration (ERDA) and, today, the Nuclear Security Enterprise (NSE) under the National Nuclear Security Administration (NNSA) and the U.S. Department of Energy (DOE).

The INMM also has well-established international roots, with ten international chapters, as well as two international student chapters, and an international presence with more than 40 percent of its 1,400-plus members now residing outside the United States. The Institute's international collaborations also extend across a broad range of organizational entities, including the Brazilian-Argentine Agency of Accounting and Control of Nuclear Materials (ABAAC); the Australian Nuclear Science & Technology Organization (ANSTO); the European Safeguards Research and Development Association (ESARDA); the European Atomic Energy Community (EURATOM); the International Atomic Energy Agency (IAEA); the Nuclear Threat Initiative (NTI); and the World Institute for Nuclear Security (WINS[1]), to name a few.[2]

INMM's mission is accomplished through six technical divisions and sixteen chapters established both in the U.S. and internationally. There are six U.S.-based regional chapters that provide federal, national laboratory, and private sector members with venues for collaboration, as well as the ten previously mentioned international chapters. The INMM also has fourteen active student chapters, engaging the next generation of nuclear stewards in the critical science, technology and policy issues facing the global nuclear community, including two international student chapters.

In addition to the work performed by the technical divisions, discussed later in this column, there are numerous committees and other functions supporting the mission elements of the Institute including:

- INMM's American National Standards Institute (ANSI) Standards Committees are the Accredited Standards Development Organization (SDO) for ANSI Standards **N-14** (*Packaging and Transportation of Radioactive and Non-Nuclear Hazardous Materials*), and **N-15** (three standards – *SNM Control and Accounting Systems for Nuclear Power Plants*; *Measurement Control Program*, *NDA Measurement Control and Assurance*; and *Measurement Control Program, Nuclear Materials Analytical Chemistry Laboratory*). INMM members contribute to the development and updating of these two standards.
- INMM's Education and Training Committee works with many organizations, including international groups such as ESARDA, to develop educational materials and opportunities for professionals worldwide; and supports educational institutions to promote the nuclear profession, as well as the development of the next generation nuclear professionals.
- The INMM has published a peer-reviewed *Journal of Nuclear Materials Management* (*JNMM*) for more than forty years. Recognized in the industry as a source of credible scientific, technological, and policy research, the *JNMM*, as well as other communication resources such as the Web-based INMM *Communicator*, LinkedIn, and other social media, provide the conduits for the INMM to reach out to a broad segment of professionals worldwide to disseminate information, provide a venue for academic and scientific collaboration, and serve as a repository for an extraordinary historical information database spanning more than five decades.

INMM Technical Divisions Provide the Expertise Needed to Sustain the Mission

INMM's six technical divisions include some of the world's leading nuclear scientists, engineers, and policy professionals, engaged in collaborative efforts to promote and advance research in the field of nuclear materials management.

- **Facility Operations Technical Division —** This is the newest INMM technical division, providing a forum for an exchange of knowledge, best practices, and lessons learned among those involved in nuclear facilities' operations in both commercial and government sectors. This division is committed to the promotion and advancement of safe and secure nuclear material operations in reactors and processing facilities throughout the world. The division's focus includes activities and information related to complete fuel cycle operations from mining through final product, and all phases of nuclear material operations, including planning, management, and storage.
- **International Safeguards Technical Division —** The ISD provides a forum for the exchange of information on the continuing development of international safeguards within the nonproliferation regime and for the enhancement of a broad understanding of the implementation and effectiveness of safeguards. The division examines technical issues, facilitates publication of studies related to safeguards, and supports workshops on the advancement of safeguards technology and procedures, such as the highly successful INMM/ESARDA Joint Workshop, *Future Directions for Nuclear Safeguards and Verification*, held in Aix-en-Provence, France on October 12-20, 2011.[3]
- **Material Control and Accountability (MC&A) Technical Division —** The MC&A Division promotes communication, professional development and the exchange of technology among professionals active in the control and accountability of nuclear materials. Workshops are frequently sponsored by the MC&A Division, such as the *International Workshop on Best Practices in Material Holdup Monitoring* that has served as a rich source of information for the MC&A community for years.[4]
- **Nonproliferation and Arms Control Technical Division —** This division promotes the advancement of research and development efforts in support of international arms control and nonproliferation through the application of nuclear materials research and management to arms control, nonproliferation, and treaty verification, as well as to transparency measures aimed at furthering international stability.
- **Nuclear Security and Physical Protection Technical Division —** This division promotes the advancement and implementation of technology and systems for the physical protection of nuclear materials and facilities. The division is the focal point for information and activities related to the physical protection of nuclear materials, nuclear facilities, and other high value assets and facilities. The division has three areas of activity, Performance Assurance and Testing, Nuclear Infrastructure Security, and Human Reliability, which are supported through standing committees.
- **Packaging, Transportation, and Disposition Technical Division —** This newly formed technical division combines the work of the previous Packaging and Transportation and the Waste Management Technical Divisions. It promotes the advancement of technology involved in the packaging, transportation and waste management of radioactive materials and its successful application to problems around the world.

The INMM's Technical Division Web page, http://www.inmm.org/Technical_Divisions/3372.htm, provides links to useful technical information in these subject areas, including division overviews and tutorials, as well as contact information for division leadership if you have any questions or are seeking additional information.

One Challenge Facing the INMM: U.S. Restrictions on Conferences and Meetings

As many of you already know, this past year the U.S. Office of Management and Budget (OMB) provided guidance to U.S. federal agencies to ensure that federal funds are used for purposes that are "appropriate, cost effective, and important to the core mission of federal agencies." This guidance requires that DOE and NNSA more closely monitor their involvement in conferences and meetings where the agencies have a major supporting role. This monitoring, and the resulting restrictions, impacted the Annual Meeting this year through last-minute cancellations, not only by federal staff but also participants from the U.S. national laboratories and their supporting contractors. Institute leaders are aggressively addressing this issue with DOE and NNSA in an effort to minimize its impact in the future. Many other prestigious professional organizations, including the American Association for the Advancement of Science, the American Physical Society, and the American Chemical Society are also expressing their concerns about these new restrictions to their federal agency supporters and the U.S. Congress.

The important academic, scientific, and technical collaborations that are so fundamental to the accomplishment of the Institute's mission are jeopardized by these new restrictions, and it is up to all of us as members of the Institute to use our spheres of influence to ensure continued support for the INMM Annual Meeting, sponsored workshops and other events. The information above represents only a small snapshot of the critical mission performed by the Institute, but one that we hope is carried forward by you in as many venues as possible.

We encourage JNMM *readers to actively participate in these strategic discussions, and to provide your thoughts and ideas to the Institute's leadership. With your feedback we hope to explore these and other issues in future columns, addressing the critical uncertainties that lie ahead for the world and* *the possible paths to the future based on those uncertainties. Jack Jekowski can be contacted at jpjekowski@aol.com.*

Notes

1. See the *JNMM* Summer 2011, Volume XXXIX, No. 4, 12-18, *Promoting Best Practices in Nuclear Security through the World Institute for Nuclear Security*.
2. The INMM Strategic Planning Committee (SPC), in collaboration with INMM leadership, is compiling a "Collaboration Matrix" that identifies existing, planned, and potential organizational relationships with entities that have like interests to those of the INMM. More than forty organizations have been identified to date, and more are being added as discussions on this data grow. The SPC will prioritize this list and identify strategic opportunities where collaborations may be strengthened, expanded or established as part of an overall effort to leverage the resources of the Institute to accomplish its mission.
3. See the *JNMM* Winter 2012, Volume XL, No. 2, 57-59, *Taking the Long View* column for more detailed information on this international conference.
4. See the *JNMM* Winter 2008, Volume XXXVI, No. 2, for a number of peer-reviewed articles on nuclear material holdup and a report on the international conference held at Oak Ridge National Laboratory in 2006.

Author Submission Guidelines

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

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

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

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

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Managing Editor
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Deerfield, IL 60015 USA

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

Format: All papers must include:

- Author(s)' complete name, telephone number and e-mail address
- Name and address of the organization where the work was performed
- Abstract
- Camera-ready tables, figures, and photographs in TIFF, JPEG, or GIF formats. Black and white only.
- Numbered references in the following format:
  1. Jones, F. T. and L. K. Chang. 1980. Article Title. *Journal* 47(No. 2): 112–118. 2. Jones, F. T. 1976. *Title of Book*, New York: McMillan Publishing.
- Author(s) biography

JNMM is published in black and white. **Authors wishing to include color graphics must pay color charges of $700 per page.**

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

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

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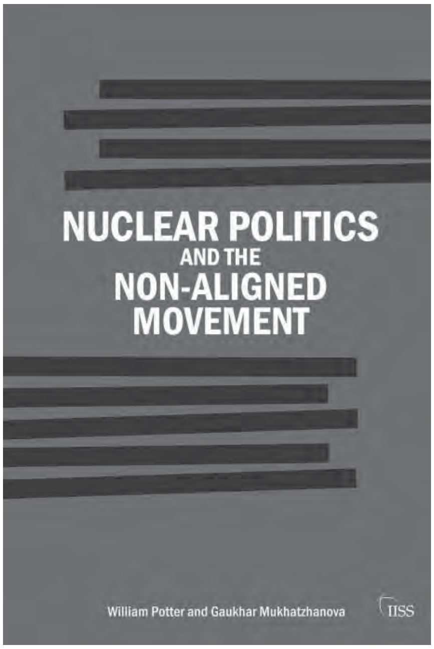
Book Review

By Mark L. Maiello
Assistant Book Editor

Nuclear Politics and the Non-Aligned Movement
Author: *William Potter and Gaukhar Mukhatzhanova*
Routledge, Abingdon and New York
ISBN 978-0-415-69641-8

The Non-Aligned Movement (NAM), contend the authors of this book, is a little-understood group of nations that is looked upon inaccurately and somewhat superficially by the nuclear weapons states (NWS) who must deal with it. Deciding not to learn the ways and means of the NAM could be perilous because this large collective (120 nations) can exert formidable power in the forums where it operates. Without consideration of the NAM's long-standing aspirations and current concerns, NWS' goals are most likely unachievable or they will be won at an exorbitant price. Compromise, diplomacy, and negotiation are key to unlocking the movement's cooperation.

NAM members are devoted to, among other things, nuclear technology transfer unfettered by nonproliferation restrictions and the inalienable right to peaceful nuclear development. Non-Nuclear Weapons States (NNWS) see unfair and one-sided hindrances erected when nonproliferation restrictions are emplaced especially without their consultation. And of course, an overarching theme remains the NAM demand for the NWS to adhere to the Nonproliferation Treaty (NPT) resolution for nuclear disarmament or at the least to demonstrate continuing progress towards this end. The authors explore the administration of this large and disparate collective, how it can reach consensus given the many viewpoints and national agendas it must contend with, and how it has endured since 1961 when world politics were very different.



A publication of the International Institute for Strategic Studies in London, this book explains the principals and philosophy of the NAM by citing examples of the movement's recent behavior at international nonproliferation forums. For example, an entire chapter is devoted to NAM's participation in the 2010 NPT Review Conference. Another considers NAM involvement in the International Atomic Energy Agency (IAEA). As such, the authors achieve their goal admirably despite the modest assertion in their acknowledgements that this attempt only "scratches the surface." Their writing is clear, engaging, and apparently objective. Both the negative and positive attributes of the organization are discussed frankly. The reader need not fear the word *politics* in the title. Though the machinations of consensus building at the NPT and IAEA forums are no doubt byzantine, the authors keep the explanations straightforward. The reader is obligated to pay attention, of course, but will be rewarded with a concise essay of only 192 pages. There are no illustrations in this publication and, as one would expect from a study of international relations, no technical or engineering information associated with weapons or weapons material. Two appendices listing current NAM members including observer states and another listing the dates and locations of past NAM conferences are of modest value. Twenty-three pages of notes provide background information for the four chapters and conclusion. A major flaw, despite the book's relatively small size, is the lack of an index.

Chapter one provides a fine overview of the NAM's history, structure, leading members, and decision-making process. For this reviewer, chapter three, "Peaceful Uses and Beyond: NAM in Vienna," in which the authors analyze recent NAM activity in the context of the annual IAEA General Conference was the most straightforward and therefore the most illustrative of NAM procedures, resolution-making capabilities, vulnerabilities, and intra- and extra-mural interactions. Insights are provided into the NAM approach to peaceful nuclear uses, nuclear proliferation and security, the issue of conversion from highly enriched uranium, the Iran nuclear program, and Israeli nuclear capability.

The NAM considers itself a voice for the "southern tier" of poorer, less technology-rich states with the advanced members such as South Africa acting as NAM leaders. The collective attempts to respond to these and other issues with one voice though not without much internal compromise and the concurrent pressure to hold dear to the main tenants of the movement. Intramural issues, particularly the analysis of Iran assuming the chairmanship of the NAM in 2012 is most interesting. The authors draw upon the only other analogous situation of Cuba's ascendency to the chair in the late 1970s for comparison. Cuba was an effective leader, successfully separating its duties from its national agenda. NAM nations prepared reactions to Iran's potential use of the movement to advance a national agenda. For Iran, a NAM chairmanship legitimizes its world standing and gathers around it potential allies. It does however put Iran, a nation already under UN sanctions, under deeper scrutiny not only by the West, but by NAM nations that ordinarily would not pay it nearly as much attention.

Chapter two covers NAM's work at the 2010 Nonproliferation Treaty Review Conference but specifically highlights a moment fifteen years earlier at the same meeting when the NPT was up for extension. The description of the NAM role in 1995 is illustrative of the movement's influence and the manner in which its leading states managed a consensus when consensus seemed unattainable. The skillful diplomacy and recently attained moral rectitude of newly minted NAM member South Africa proved to be the foundation on which the structure of the treaty extension deal was constructed. Five years later, several key members of NAM were responsible for agreement on the 2000 NPT Review Conference Final Document. In this example of NAM influence and importance, a working group calling itself the New Agenda Coalition formed from NAM and non-NAM member states provided a platform of reasonable discussion while remaining united in their objective of achieving greater progress on disarmament. By including such NAM members as Egypt, South Africa, and Mexico, the negotiated final document held great meaning for other NAM members who eventually accepted it.

In the final chapter, a discussion of the future of NAM includes concerns about intramural disparity on NPT and IAEA issues. However, the authors contend that NAM members continue to hold true to the disarmament and peaceful use objectives of the coalition and that loyalty should not be underestimated for possible exploitation by NWS. As the future unfolds, the organization's ability to provide a cohesive voice for its members while maintaining core aspirations will be scrutinized. A telltale issue includes the internal rift revealed over the U.S.-India nuclear deal. Others are the Arab states' concern over Israel's nuclear capabilities and the establishment of a Middle Eastern weapons free zone, both something of "hot button" issues at the 2010 NPT Review and IAEA General Conferences.

The authors repeat a theme that urges the agents and diplomats of the NWS to understand the motives of the NAM and to reach out to its members (or at minimum to its leading members) through negotiation and discussion. To that end, the reader of this book will obtain concise information about an important organization that the authors contend has been overlooked by many scholars. This fine work of Potter and Mukhatzhanova ends that unfortunate oversight.

Mark L. Maiello, PhD, is a former U.S. DOE scientist with an interest in radiological and nuclear security. He is a member of the Arms Control Association, a co-editor of the book Radioactive Air Sampling Methods *(CRC Press, 2010) and has served as a contributing editor at* Health Physics News *for nine years. He us currently employed as a health physicist.*

Edway R. Johnson
December 13, 1927 – November 28, 2012

While not one of the original members, Edway R. Johnson is nonetheless considered one of the founding fathers of the INMM, as he had a huge impact on the formation and development of the INMM. Ed became a member in 1961 and became a Senior Member in 1983. He was elected as a Fellow in 1986. Ed was elected to and served on the Executive Committee of the INMM as a Member-at-Large on several occasions, as vice president (1963-1964), and as president (1965-1966). He served as chair of the Waste Management Technical Division from its formation in 1982 until 2010. He was a member of the Awards Committee (1989-2010). Ed also served as chair of the N15 ANSI Standards Committee for several years.

As chair of the Waste Management Technical Division, Ed organized twenty-six major seminars on spent fuel management, the first held the year that the U.S. Congress passed the Nuclear Waste Policy Act. Ed led a team of nuclear professionals to the People's Republic of China in 1983 as part of technical exchanges under the People-to-People program. Ed served on a number of ad hoc committees for the Institute, including the Fellows subcommittee to develop a response to the challenge issued by the Nuclear Threat Initiative to INMM to develop an educational forum for nuclear materials management. This work led to a proposal outlining what has become the World Institute for Nuclear Security (WINS).

Ed served on an ad hoc committee dedicated to search for administrative support to the Institute when the then-contracted association management firm on short notice decided to no longer support INMM. With insufficient time to make a reasoned decision on a replacement, Ed, supported by his very talented wife Jerry, came to the rescue of INMM and traveled to Columbus to retrieve the INMM records and take them back to their offices in Washington. They managed and supported the organization, at no charge, until it was able to establish a contract with a new association management firm. Had it not been for this support, it is not clear what the history of INMM would have been.

Ed was the recipient of the Institute's Distinguished Service Award in 1987 based on his service to the organization. In 2010, the Institute's Meritorious Service Award was renamed the Edway R. Johnson Meritorious Service Award in his honor. He was the first recipient of the renamed award based on his many decades of contributions and leadership in INMM and in the field of nuclear materials management.

Despite this impressive contribution to the Institute, the list does not contain his most important contribution. He was the consummate mentor, constantly taking actions to involve young professionals in the operations of the Institute. Because of his efforts, numerous individuals advanced to leadership positions. More than just talking about development of the next generation of nuclear professionals, he was tireless in his efforts to actually accomplish it. His mentoring and help was not limited to the younger members of the organization; anyone who worked in the Institute or held office appreciates the mentoring and support they received from Ed.

Ed was a graduate of Bowling Green State University with a B.S. in chemistry. He began his nuclear career as a chemical analyst and development chemist at the Atomic Energy Commission plant at Fernald, Ohio (1952-1957), where uranium ore was processed to metal slugs for use in weapons plutonium production. He was later technical director and subsequently vice president of Nuclear Fuel Services, where he was involved in the development of nuclear fuels for test reactors, commercial power and naval applications. His duties also included reprocessing of BWR, PWR, HTGR, and NPR fuels, including the transport of these materials (1957-1967). In 1964, he formed E. R. Johnson Associates, an engineering firm, which later evolved into JAI Corporation. Assuming the office of president and chair of this company in 1967, he oversaw JAI's service to clients worldwide in studies related to design of processes and facilities in the various steps of the nuclear fuel cycle, waste management, transportation, safeguards and security, safety and licensing, and economic analysis. From 1970-1975, he also formed and was president of Nuclear Chemicals and Metals Corporation, which processed thorium nitrate into oxide and metal.

Ed was also a member of the American Chemical Society, the American Nuclear Society, the American Institute of Chemical Engineers and the American Society of Metals. For more than twenty years, he served on the Radiation Advisory Board of the Commonwealth of Virginia. He authored or co-authored more than 100 papers and documents regarding nuclear material process technology, economics, safeguards, security, transportation and waste management.

Ed is survived by his wife of fifty years, Geraldine (Jerry) Love Johnson, and seven children: Melinda Johnson Emery, Deborah Johnson Sutton, Jillanna Johnson Lane, Marianna Johnson, Lt. Col. Edway R. Johnson II, Constance Johnson Barton and Lt. Col. Theodore A. Johnson.

The Johnson family has asked that in lieu of flowers contributions be made to the Edway R. and Geraldine L. Johnson Scholarship for Science at Bowling Green State University, Bowling Green, Ohio 43403, which gives scholarships to outstanding young people in the sciences.

Calendar

April 2–3, 2013

Seventh Annual Workshop on Reducing the Risk from Radioactive and Nuclear Materials: Challenges in Nonproliferation and Arms Control
Washington, DC USA
Sponsors: INMM Nonproliferation and Arms Control Technical Division and the Northeast Chapter
Contact: Institute of Nuclear Materials Management
+1-847-480-9573
E-mail: inmm@inmm.org
Web site: www.inmm.org

May 27–30, 2013

35th ESARDA Annual Meeting
Congrescentrum Oud St. Jan
Bruges, Belgium
Sponsored by ESARDA
Web Site: http://esarda2.jrc.it/about/

July 14–18, 2013

INMM 54th Annual Meeting
JW Marriott Desert Springs
Palm Desert, California USA
Contact: Institute of Nuclear Materials Management
+1-847-480-9573
E-mail: inmm@inmm.org
Web site: www.inmm.org

August 18–23, 2013

PATRAM 2013
Hilton San Francisco Union Square
San Francisco, California USA
Hosted by the U.S. Department of Transportation, the Nuclear Regulatory Commission, and the Department of Transportation in cooperation with the INMM
Contact: Institute of Nuclear Materials Management
+1-847-480-9573
E-mail: inmm@inmm.org
Web site: www.patram.org

July 19–24, 2014

INMM 55th Annual Meeting
Atlanta Marriott Marquis
Atlanta, Georgia USA
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+1-847-480-9573
E-mail: inmm@inmm.org
Web site: www.inmm.org

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Institute of Nuclear Materials Management

INMM 54th Annual Meeting

July 14 – 18, 2013

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