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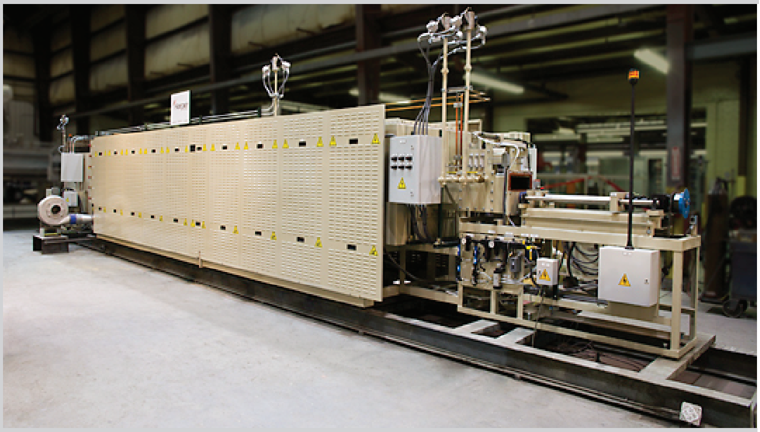

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INMM's New Mission Statement

By Larry Satkowiak
INMM President

This past summer we had a very successful Annual Meeting (AM). The number of attendees and the quality and number of papers presented exceeded all expectations. Our multi-year effort to engage students has proven successful with 139 students attending the Annual Meeting and presenting 115 papers. The total number of INMM chapters (including regional, international, and student chapters) has grown to 32 with increasing interest in nuclear materials management around the world. The conversion of the *Journal* to an all-electronic version was highly successful and was well received by the membership. We now have the "good" problem of an abundance of papers. All considered, I think the future looks bright for the Institute.

November Executive Committee Meeting—A New Mission Statement

In November, the Executive Committee (EC) met in Boston, Massachusetts. Each year, the November meeting's primary focus is developing and approving the operating budget for the Institute. Last year at this time, after two consecutive Annual Meetings with lower-than-expected attendance, the EC had to make some difficult choices and cut some of the non-technical program specific expenses. However, as mentioned above, the Atlanta AM exceeded expectations in all regards, including attendance, and the EC was able to restore some of the items that were cut, the most notable being the morning Speakers' Breakfast. Also, during the November EC meeting we reviewed the post-Annual Meeting survey to identify ways to improve the AM experience. We value the input from all of the participants. Jack Jekowski, chair of the Strategic Planning Committee, led a lively discussion on the revision of the INMM Mission Statement. After input from the extended leadership of the INMM that included the EC, Technical Division Chairs, Oversight Chairs and the Fellows, the following Mission Statement was approved:

> **INMM Mission Statement**
> The Institute of Nuclear Materials Management (INMM) is an international professional society dedicated to development and promulgation of practices for the safe, secure and effective stewardship of nuclear materials through the advancement of scientific knowledge, technical skills, policy dialogue, and enhancement of professional capabilities.

I think the new mission statement accurately and succinctly captures our current focus. My thanks to Jack and everyone involved.

30th Annual Spent Fuel Seminar

I just spent the last two and a half days participating in the 30th Annual Spent Fuel Seminar in Crystal City, Virginia, just outside of Washington, DC, USA. Congratulations to the organizers, the INMM Packaging, Transportation and Disposition Technical Division (led by Jeff England) and the U.S. Nuclear Infrastructure Council (represented by Eric Knox). The organizers did a terrific job putting together an outstanding agenda. An international group of more than 130 participants from government, industry, trade organizations, academia and professional societies presented papers, shared ideas and exchanged best practices. This workshop continues to be relevant as the nuclear industry continues to struggle with issues surrounding the disposition of commercial spent nuclear fuel.

IAEA Safeguards Symposium

In October, the INMM, ESARDA (European Safeguards Research & Development Association) and the IAEA (International Atomic Energy Agency) co-sponsored the 2014 Safeguards Symposium. The INMM International Safeguards Division (led by Michael Whitaker) assisted in organizing the quadrennial symposium. The symposium featured nearly 300 presentations and posters distributed among thirty-five technical sessions. Approximately 600 people attended the symposium representing fifty-nine countries and eleven organizations. Klaas van der Meer (ESARDA President), Tero Varjoranta (IAEA Deputy Director General for Safeguards and one of our plenary speakers at last year's Annual Meeting), and I made some opening remarks. Klaas and I outlined the missions of our respective organizations and highlighted our upcoming joint workshop. The workshop will focus on Building International Capacity and will be held October 4-7, 2015, at the Jackson Lake Lodge (Grand Teton National Park), Moran, Wyoming, USA. The workshop will feature four parallel working groups on nuclear security, arms control, international safeguards, and education and training.

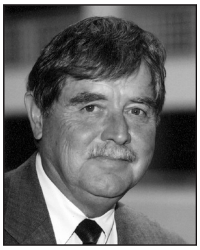
Looking Forward

In early March, the Technical Program Committee will meet to review all the abstracts submitted, sort them into sessions, and develop the technical program for the 56th INMM Annual Meeting which will be held July 12-16, 2015, in Indian Wells, California, USA.

Finally, it's with a heavy heart that I have to announce that Jodi Metzgar, the Sherwood Group (our management company) executive director for the INMM account is leaving the company. I have known and worked with Jodi for eight years and she will be sorely missed by all of us. She is leaving to be the deputy director of the International Society for Travel Medicine. We wish her all the best.

Let us welcome Aaron Adair as the new executive director. Aaron has been with the Sherwood Group for twelve years. He has most recently served as executive director for the Dermatologic and Aesthetic Surgery International League and the American Physician Scientists Association and as administrative director for the Association of University Technology Managers. In these positions, he expanded his client's portfolios to include profitable international and online educational courses, and developed innovative membership retention and recruitment programs. Welcome, Aaron!

Book Review, Taking the Long View, and More



By Dennis Mangan
INMM Technical Editor

In this issue, INMM President Larry Satkowiak begins with an interesting summary of activities that have occurred over the past year. He highlights INMM's new Mission Statement, an excellent and succinct statement that reflects what we within the INMM community have been pursuing for many years. As noted by Larry, Jack Jekowski, INMM's Strategic Planning Committee Chair, was instrumental in leading the Mission Statement development.

This issue has three articles, two by students from two universities. We are pleased to be able to publish such articles from our student population. As our president notes in his article, "Our multi-year effort to engage students has proven successful with 139 students attending our (last) Annual Meeting and presenting 115 papers." Presuming all of the 115 papers were published in the Proceedings of the Annual Meeting, which should be the case, the opportunity for students to gain exposure in the INMM technical fields is within the INMM publications.

The first student article in this issue is *Synthesis and Characterization of* Ce^{3+} *Doped Amorphous Lithium Tetraborate* authored by students from the University of Tennessee, Knoxville, Tennessee, USA. The thrust of this study is to develop potential scintillation material for thermal neutron detection, with the intent to augment the Helium-3 detection capability. The authors are reporting that progress in this study has been successful, which is quite impressive.

The second article, *Verification Challenges and Opportunities*, by Kelsey Hartigan and Andrew Newman of the Nuclear Threat Initiative in Washington, DC, USA, provides a fairly complete discussion of a two-year study resulting in key verification challenges and include recommendations governments around the world can undertake to strengthen nuclear security and nonproliferation efforts and enable future warhead reductions.

The third article is the second student paper in this issue, *Proliferation Resistance Analysis and Evaluation Tool for Observed Risk (PRAETOR)—Methodology Development* by students from Texas A&M University, College Station, Texas, USA, under the leadership of Professor William Charlton. The article goes into exceptional depth discussing the development of a computer code PRAETOR to aid in comparing the proliferation resistance of nuclear installations. (A note to readers: at the end of this article you will see that the authors and Professor Charlton have photos and a brief synopsis. This is the first time we have attempted this. The purpose is to provide more exposures to authors. Your comments would be appreciated.)

Our Book Review Editor, Mark Maiello, in his article, has provided what appears to be an excellent review of the book, *Fukushima: the Story of a Nuclear Disaster.* His review highlights some topics I never thought about in the Fukushima Disaster. The book appears to definitely be one to read.

Finally, Jack Jekowski, our Industry News Editor, and the chair of the Strategic Planning Committee, has a very interesting article on *International Collaborations Amid a 21st Century Test for Diplomacy*. You are encouraged to read Jack's article and to provide him your thoughts and ideas on the topic.

JNMM *Technical Editor Dennis Mangan can be reached* atdennismangan@ *comcast.net.*

Synthesis and Characterization of Ce^{3+} Doped Amorphous Lithium Tetraborate

John D. Auxier II, Andrew N. Mabe, Stephen A. Young, Jerrad P. Auxier, George K. Schweitzer
University of Tennessee, Knoxville, Tennessee USA

Abstract

Amorphous lithium tetraborate glass was synthesized from polycrystalline $Li_2B_4O_7$ and boric acid (H_3BO_3) for the development of a potential scintillation material for thermal neutron detection. The powders were heated simultaneously with cerium oxide (CeO_2) to produce an optically clear glass. In the presence of excess boric acid, the Ce^{4+} was reduced to Ce^{3+} creating a fluorescent center in the glass matrix without implementing a reducing atmosphere. The mechanism of this reduction is explored, in addition to a number of other investigative techniques of the composition and morphology including ICP-OES, NMR, P-XRD, and FT-IR. The optical properties of this material were probed using UV-Vis and fluorescence spectroscopy revealing an optically clear material in the region from 330 – 800 nm and a fluorescence emission peak at 360 nm.

Introduction

The detection of thermal neutrons is important to many areas of nuclear science. Helium-3 is widely used in the detection of thermal neutrons; however, due to the limited supply of helium-3, the U.S. Department of Homeland Security has expressed an interest in developing replacement technologies for thermal neutron sensing devices. Replacement technologies developed over the past few years for this purpose have included detection materials in solid, liquid, and gas form,[1] primarily as gas proportional counters, semiconductors, and scintillators. Scintillators have been developed in gaseous, single crystal, amorphous glass, liquid, and plastic form. Of these, amorphous glass is an attractive choice due to low toxicity, ease of fabrication, and that it can operate in a wide range of environmental conditions.

One of the most common scintillating glasses used to detect thermal neutrons is cerium(III)-activated lithium glass, which is sold under the commercial name GS20. This material is characterized by good neutron detection efficiency and high light yield; however, it is very expensive and the presence of large Z number elements such as Al and Mg in the matrix increase its sensitivity to gamma-ray-induced pulses that overlap with the thermal neutron pulses.[2]

In an effort to develop a material at lower cost and with a smaller average Z number, borate glasses were considered. Amorphous lithium tetraborate ($Li_2B_4O_7$, denoted as LBO) is a highly versatile material and has been used in many applications due to its piezoelectric, optical,[3,4] and scintillation properties. Cerium(III)-doped lithium tetraborate has been reported as an extrinsic scintillator in both the crystalline[5–9] and amorphous form.[9–16]

The amorphous Ce(III) doped LBO of this study incorporates ^{6}Li (7.4 wt percent) and ^{10}B (4.8 wt percent) isotopes[1,17] for thermal neutron detection[8,10] and Ce^{3+} as the scintillation center. This composition provides a potential material for thermal neutron detection due to the large thermal neutron capture cross sections of ^{6}Li (942 b) and ^{10}B (3840 b). Neutron detection occurs due to the interaction of thermal neutrons with the Li and B isotopes. The ^{6}Li produces an alpha particle ($^{4}He^{2+}$, 2.05 MeV) and a triton ($^{3}H^{+}$, 2.73 MeV), which travel through the matrix and excite the Ce^{3+} traps. A similar mechanism is employed with the ^{10}B, which interacts with thermal neutrons to produce $^{7}Li^{+}$ (0.84 MeV, 94 percent or 1.01 MeV, 6 percent) and the alpha particle (2.79 MeV, 94 percent or 2.31 MeV, 6 percent). The charged particles generate ionizations and excitations in the LBO matrix which de-excite at the Ce^{3+} traps, thereby producing scintillation light which is detectable by a photomultiplier tube.

The focus of this work is to provide the characterization of amorphous LBO glass doped with Ce(III). Ce(III) is susceptible to oxidation by oxygen in the air. Generally, the incorporation of Ce(III) into materials requires the presence of a reducing atmosphere such as Ar/H_2 or operating with the raw material in a glovebox. It is shown herein that Ce(IV) can be incorporated initially into the matrix which is subsequently reduced during melting with boric acid. Ishii *et al.*[10] have previously introduced the material's potential as a thermal neutron detector due to its robust qualities; thus, the focus of this work will be to show the chemical and morphology characterization of this material as well as to provide a possible method by which Ce(III) and Eu(II) doped glasses can be synthesized without the use of a reducing atmosphere or operating in a glovebox.

Materials and Preparation Methods

The Ce(III)-loaded LBO ($^6Li_2B_4O_7$) glass samples were prepared from lithium hydroxide (^6LiOH) supplied by B&W Technical Services Y-12, LLC (formerly BWXT Y-12). The $^6LiOH \cdot H_2O$ was purified by dissolving in MeOH (Fisher) at 13g/l at 75°C, then filtering through a 2 μm filter and drying the filtrate in a vacuum oven at 150°C. The boric acid (H_3BO_3) (Fisher Scientific), $Li_2B_4O_7$ (natural abundance Li) (Alfa Aesar) and cerium (IV) oxide (Sigma); all were used as received with no further purification.

Polycrystalline lithium carbonate was synthesized by reacting the lithium hydroxide in aqueous solution[18] with powdered CO_2. The ^6LiOH and CO_2 were initially combined in a ratio of 1:4 to form lithium carbonate. The pH was monitored and kept above 10.3 with excess lithium hydroxide to prevent the formation of the bicarbonate species.[18] The lithium carbonate was then reacted with boric acid in an alumina crucible for four hours at 400°C, according to previously reported methods.[19] The resulting solid was ground with a mortar and pestle and was then heated at 750°C to melt the components. On cooling this process produced polycrystalline lithium tetraborate, confirmed by powder X-ray diffractometry (PXRD) characterization.

Vitreous Ce(III)-loaded lithium tetraborate was prepared by combining the polycrystalline lithium tetraborate with boric acid (17 wt percent) (0.850 g, 13.7 mmol) and doped with varying amounts of Ce (IV) (via CeO_2), ranging from 0.5 – 5.0 wt percent and placed in a graphite crucible at 1,050°C for one hour under normal atmosphere to melt the components. The temperature ramp was 40°C/min until 850°C, at which point the ramp rate was reduced to 10°C/min until the 1,050°C temperature was obtained. The crucible was then placed in a nitrogen atmosphere vacuum oven (0.003 atm) and cooled to room temperature. The resulting glass samples discussed herein were 2 mm thick and 2.5 cm in diameter and contained 0.5 wt percent Ce and 17 wt percent boric acid; all samples were water-polished using silicon carbide sandpaper of 600, 800, and 1,200 grit. The doped samples henceforth will be referred to as LBO:Ce.

Characterization Methods

The LBO:Ce was characterized by a number of methods to determine the elemental composition, opacity, morphology, and surface characteristics of the material.

Elemental composition was determined using a Perkin-Elmer Optima 2100DV Inductively Coupled Plasma—Optical Emission Spectroscopy (ICP-OES) after samples were dissolved in hydrofluoric acid (50 percent, Acros) and diluted with 2 percent HF in polyethylene volumetric flasks. Powder X-Ray Diffraction (P-XRD) was performed using a Panalytical Empryean X-ray diffractometer using a Pixcel 3D detector with a slit window of 1/4°2θ over a range of 5 2θ to 70 2θ. Solid State Nuclear Magnetic Resonance—Magic Angle Spinning (SS-NMR-MAS) was performed using a Varian Inova 400 MHz instrument with a Varian-Chemagnetics 5 mm double resonance MAS probe. The boron experiments were performed[20–23] using B-11 NMR with boric acid as a standard. The ^7Li NMR experiments were performed using a lithium chloride standard. Fourier Transform—Attenuated Total Reflectance—Infrared Spectroscopy (FT-ATR-IR) was analyzed using a Perkin-Elmer Frontier FT-IR-ATR Spectrum 100 over the range from 400–4,000 cm^{-1}. Images shown were taken with a Confocal Laser Scanning Microscopy (CLSM) and a Scanning Electron Microscope (SEM). UV-Vis spectroscopy and band gap measurements were performed using a Perkin-Elmer Evolution 600 UV-Vis spectrometer in which the spectral bandwidth was 5 nm. Fluorescence measurements were performed using a Perkin-Elmer LS-55 fluorescence instrument. The emission and excitation experiments were performed with a detector gain of 750 kV and a spectral bandwidth of 5 nm. Excitation and emission spectra were corrected for the spectral sensitivity of the detector PMT.

Results

Optical Characterization

The optical transparency and band gap of the LBO:Ce material (Figure 1) was probed with UV-Vis spectroscopy by scanning over the wavelength range 200–800 nm. The uncorrected UV-Vis results indicated nearly identical transparency (Figure 2) between the undoped LBO glass and the 0.5 wt percent CeO_2 glass; note a minor loss of transparency for the Ce doped glass in the 400 to 500 nm wavelength. Optical transparency for the LBO:Ce material was calculated from uncorrected spectra to be between 75 percent and 80 percent in the 500 to 800 nm wavelength range (Figure 2). The UV-Vis spectrum reveals that

Figure 1. A picture of the 0.5 wt percent Ce lithium borate glass

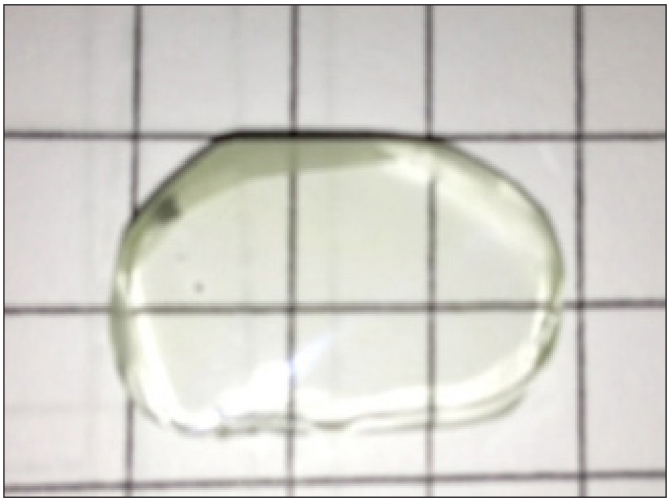


Figure 2. UV-Vis spectra of undoped and 0.5 wt percent CeO_2 Ce doped lithium tetraborate glass

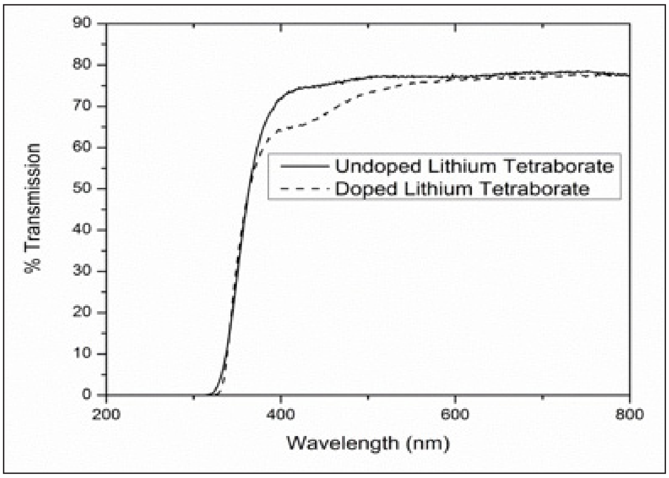
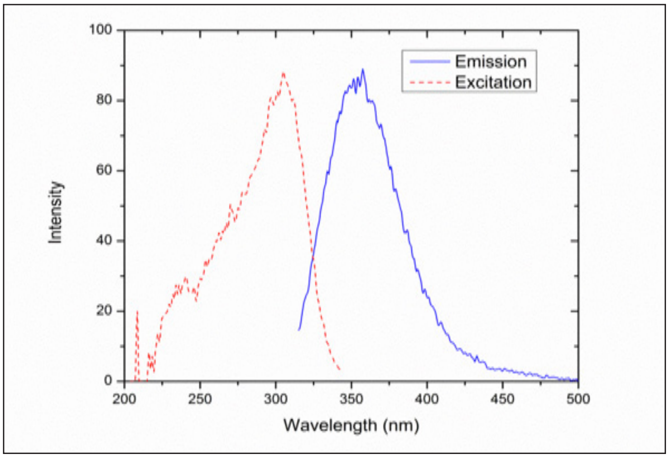


Figure 3. The fluorescence profile of lithium tetraborate doped with 0.5 wt percent CeO_2, 17 wt percent boric acid



the samples have high optical transparency in the range from 400 to 800 nm with a decrease in transparency at 330 nm.

The band-gap of this material is especially important to determine the ability of the charged particle decay energy to migrate in the matrix from the fission center to the scintillation center, the Ce^{3+} ion. The determination of the band-gap is described by Perkin-Elmer.[24] The band-gap for both materials, the doped and un-doped lithium tetraborate is similar, with the undoped lithium tetraborate having a band-gap of 3.75eV and the 0.5 wt percent Ce doped glass having a band-gap of 3.7 eV. The doped source has increased absorbance in region from 380 to 460 nm likely as a result of the absorption of Ce^{3+} in this region. The slight yellow color of the doped sample comes from an incomplete reduction of the Ce^{4+} to the Ce^{3+} state, thus resulting in absorption in this region.

Cerium Method of Interaction/Fluorescence Results

The method of interaction of the Ce^{4+} in the LBO material is described by Hao and Gao.[25] To summarize, as the Ce^{4+} ions enter the LBO material, a single Ce^{4+} ion (center), replaces four Li^+ centers in the lithium tetraborate network. This substitution maintains electroneutrality in the LBO material. It is further discussed that the removal of the lithium centers creates an abnormal vacancy in the structure allowing an electron donation from the *s* orbital of the BO_4^{-1} ring to the Ce^{4+} center resulting in stable Ce^{3+}. The Ce^{3+} has been observed[25] for both crystalline and non-crystalline lithium tetraborate matrices doped with cerium (Ce). The reaction in the LBO:Ce mixture occurs as the material is heated. The single Ce^{4+} center replaces four Li^+ centers in the lithium tetraborate and creates an abnormal aliovalent vacancy in the structure as discussed. The stable Ce^{3+} then becomes a fluorescent center in the LBO:Ce material.

The effectiveness of the reduction of the Ce^{4+} to Ce^{3+} varied with the boric acid loading in the samples. Optimal boric acid quantity was determined to be 17 wt percent by varying the amount of boric acid in the LBO:Ce samples and measuring the fluorescent intensity versus the boric acid concentration. From the experiments, it was determined that higher loadings (beyond 17 percent) of boric acid introduced increasing amounts of crystallinity into the glass structure which is an undesirable effect for optical materials.

A series of experiments was also performed to determine the optimal concentration of Ce in the matrix to achieve the fluorescence intensity. Glasses were prepared using lithium tetraborate, 17 wt percent boric acid, and various amounts of CeO_2. The fluorescence profile of the final material is shown in Figure 3.

The LBO:Ce, with the above concentrations, was observed to have strong absorption near 310 nm with a maximum emission near 360 nm. According to Elias,[26] the trivalent Ce has a ground state that is split by spin-orbit coupling to give two ground states, the $^2F_{7/2}$ and the $^2F_{5/2}$. Upon excitation by high-energy particles or photons, electrons and holes are generated in the matrix. Upon coming into proximity with a Ce^{3+} center, a single 4*f* electron on the Ce^{3+} center is excited to the 5*d* shell, which subsequently relaxes producing an optical photon. Fluorescence spectroscopy, as shown in Figure 3, verified the effectiveness of the reduction of Ce^{4+} to Ce^{3+}. It is assumed that there is a direct correlation between fluorescence light output and scintillation light output; therefore an increase in the number of fluorescent centers should give an increase in the light output from scintillation mechanisms.

Elemental Analysis

Verification of the elemental composition of the LBO:Ce material was performed with the ICP-OES. The samples were found to contain 0.219 mmol of boron and 0.0989 mmol of lithium. The ratio of lithium and boron 1:2.21. This ratio is in agreement with the boron to lithium ratio, which was estimated to be 1:2, of the mixture of lithium tetraborate ($Li_2B_4O_7$) and lithium borate ($Li_3B_5O_9$). Henceforth, the glass is referred to as lithium borate. Since excess boric acid was added to the matrix, the excess of 10.5 percent is in good agreement with the ICP-OES data. The glass analyzed was lithium tetraborate with 17 wt percent boric acid and 0.5 wt percent CeO_2.

The SS-NMR results provide insight into the chemical structure of the LBO:Ce matrix. The ^7Li, ^{11}B, and ^1H nuclei were studied using H_3BO_3 and LiCl as standards[20–22,27–30] for the NMR[31,32] experiments. The boric acid has trigonal boron that is connected to three –OH groups. The results of the ^{11}B NMR show a triplet feature centered between 45 and 30 ppm. To reduce the effect of the nearby hydrogens, the Cross Polarization — Magic Angle Spinning (CP-MAS) NMR was performed. The experimental results of a boric acid standard showed a single peak at 33 ppm, demonstrating a trigonal boron species bonded to 3 oxygen groups. The ^1H groups were excited and the energy was transferred to the ^{11}B nucleus, eliminating the observed splitting. Mackenzie *et al.,*[28] and Sen *et al.,* [27] report the boric acid isotropic chemical shift (δ_{iso}) should be at ~19 ppm, however their measurements were made using a boron trifluoride etherate ($BF_3 \cdot Et_2O$) standard (δ_{iso} = 3.2 ppm). These experimental methods were used to interpret the SS-NMR information of the lithium tetraborate spectrum.

Figure 4. The proposed monomer unit of lithium borate

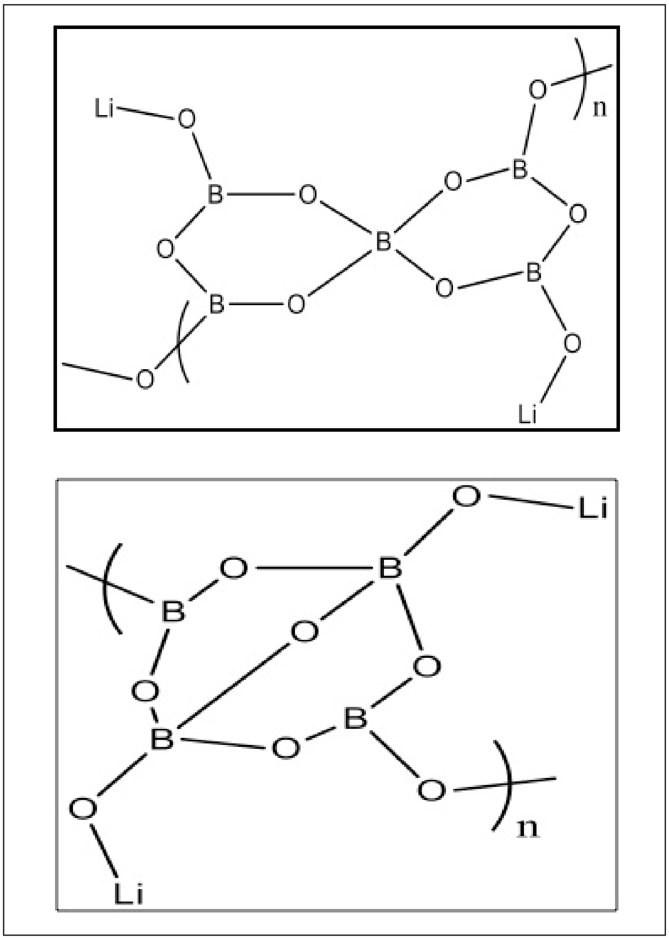


Figure 5. Lithium borate glass, doped with 0.5 wt percent Ce and 17 wt percent boric acid, B-11 SS-NMR result

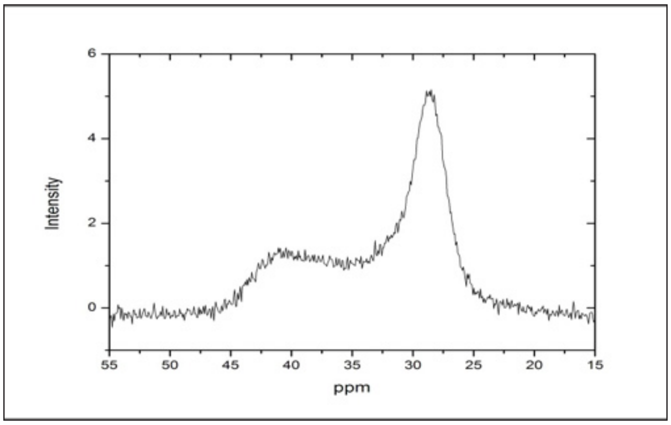
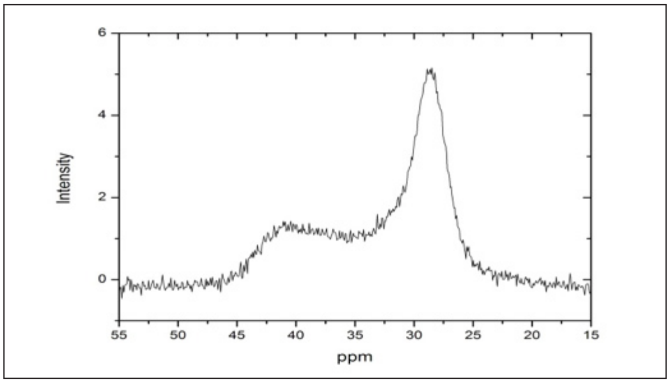


Figure 6. Ce^{3+} stabilized in amorphous lithium tetraborate matrix



Work by Byrappa[33,34] *et al*. and Touboul[35] *et al*. indicated that lithium borate, upon heating and cooling, will form optically opaque crystalline regions and an amorphous matrix, both with the chemical formula of $Li_2B_5O_9$. The amorphous motif is thought to have the structural form of a single tetrahedral boron connected to four oxygen atoms. The oxygen atoms are connected to trigonal boron species to form a ring with the chemical formula of B_3O_3. This structure is shown on left in Figure 4. Single crystal work by Senyshyn *et al.*[36] and Chen *et al.*[37] proposed that the single crystal structure and that of the amorphous substance is more likely to take the structure that is proposed on the right in Figure 4.

The structure thought to be obtained by Byrappa is on the left. The structure proposed by Senyshyn is shown on the right.

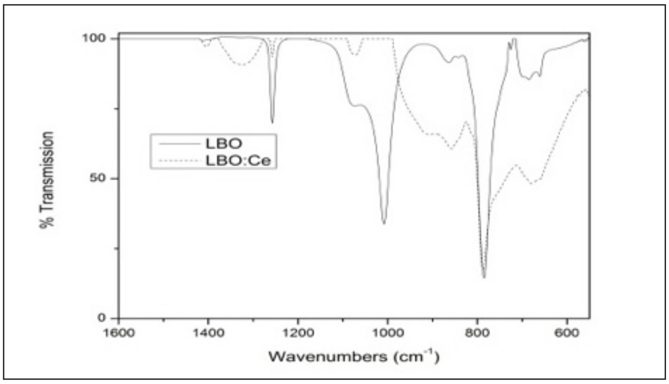
The amorphous structure, when doped with CeO_2 comprises these $Li_2B_5O_9$ repeat units.

The SS-NMR spectra shown in Figure 5 shows a trigonal boron species observed at 29 ppm and the tetragonal species is observed at 41 ppm. Integration of these peaks gives a resulting ratio of trigonal boron to tetragonal species of 3.95:1, which is in agreement with the predicted stoichiometry of trigonal boron to tetragonal boron of 4:1.

An additional explanation of the spectrum in Figure 5 is also present in the literature. Mackenzie *et al.*[28] points out that the peak at 29-30 ppm corresponds to a $(BO_3)^{3-}$ or $(BO_4)^{4-}$ species that does not form the boraxyl rings as shown in Figure 3, and would correspond to the tetragonal boron. They further discuss that the peak at 42 ppm would correspond to the trigonal boron species in the boroxyl rings. Both explanations agree with the data acquired from the FT-IR-ATR experiments and the ICP-OES experiments and are indicative of an amorphous product.

When Ce^{4+} is introduced into the matrix, it is thought to be stabilized by two B_2O_3 rings, which creates a Ce^{3+} ion assumed to have eight (shown) or nine coordinate atoms as seen in Figure 6. To maintain electroneutrality, the Ce^{3+} ion must replace four lithium ions in the matrix, whereupon the borate rings (B_3O_3) will stabilize the Ce^{3+} ion. This replacement action is consistent with the work of Hao and Gas,[25] where it is theorized[25] that the *s* electrons from the borate ring will be donated to the 4*f* shell of the Ce. In this way, the Ce will have the fluorescent capability of the 5*d* to 4*f* transition.[17]

Figure 7. The FT-IR-ATR Spectra of blank lithium borate glass (denoted LBO) and the lithium glass doped with 0.5 wt percent CeO_2 and 17 wt percent boric acid (denoted LBO:Ce)

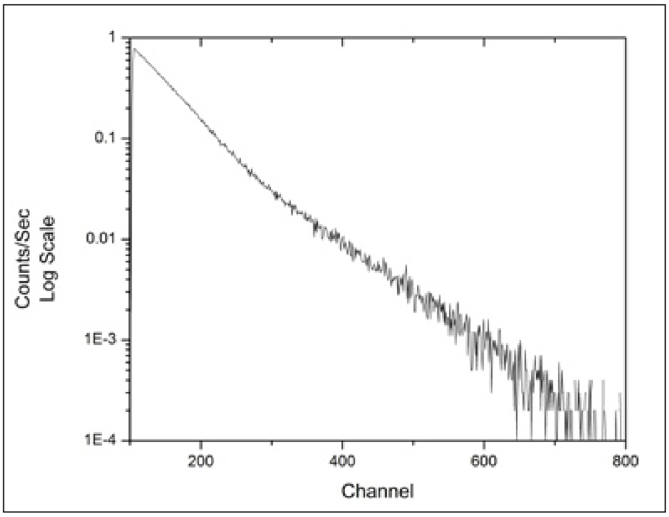


To verify the presence of a single lithium environment, ^7Li SS-NMR was performed and a single peak at 0.4 ppm was observed verifying the presence of a single lithium environment.

The FT –IR–ATR Spectroscopy was used in conjunction with the results from the SS-NMR and the P-XRD results. It was also used to probe the possible IR transition due to the loading of the Ce(III) into the material.

In Figure 7, the peaks at 640-680 cm^{-1} correspond to the plane bending of boron oxygen triangles. The peaks between 850-865 cm^{-1} corresponds to the stretching vibrations of tetrahedral $(BO_4)^{4-}$, the peaks between 1,245-1,307 cm^{-1} correspond to the stretching vibrations of $(BO_3)^{3-}$, and the peaks between 1,248-1,343 cm^{-1} correspond to the B-O stretching vibrations in the trigonal units.[38] The peak at 780 cm^{-1} represents the plane bending motion about the BO_4 sites and occurs in both the doped and un-doped samples. The peak at 1,050 cm^{-1} in the updoped sample corresponds to the B-O stretching frequencies in the BO_3 sites. This feature is shifted down to 900 cm^{-1} in the doped samples. In the spectrum, the plane bending motions of the boron-oxygen plane are greatly intensified by the presence of the Ce doping, since the peak at 582 cm^{-1} is greatly increased. The (BO_4) stretching vibrations, peak 858 cm^{-1}, are also more intense in the doped sample than in the un-doped

Figure 8. Thermal neutron response of the 0.5 wt percent Ce doped LBO glass



sample. Also the peaks at 1,324 cm^{-1} and 1,404 cm^{-1} are observed in the doped spectrum, but are not observed in the undoped sample.

Neutron Irradiation

Neutron irradiation measurements were conducted previously described by Mabe *et al* and Sen *et al.*[39,40] Samples coupled to a photomultiplier tube, then covered with a Teflon tape reflector. A moderated mass of 0.59 µg 252Cf was used as the neutron source. Thermal neutron response was determined by first irradiating the sample inside an acrylic tube 1.6 mm thick surrounded by 1.6 mm of lead to obtain the scintillation response to gamma-rays and all neutrons. The sample was then irradiated in an acrylic tube surrounded by a 1.6 mm thick sheet of cadmium to shield thermal neutrons and measure the response to gamma-rays and fast neutrons. The number of gamma-rays shielded by the lead tube is similar to the number of gamma-rays shielded by the cadmium tube. Spectral subtraction was then used to obtain the net thermal neutron response. It should be noted that the number of gamma-rays inside the cadmium tube is slightly higher than inside the lead tube due to the ^{113}Cd(n,γ) ^{114}Cd capture reaction and because the number of gamma-rays shielded by the lead tube is slightly greater than that shielded by the cadmium tube. The light pulses from the samples were converted into electrical pulses using a Philips 2202B PMT mounted on a Canberra 2007P base powered by an ORTEC 556 high voltage power supply set at 1,200 V. The signals from the base were amplified using an ORTEC 572A amplifier set at 50G with a 2 µs shaping time. The amplified signal was digitalized using an ORTEC 926 MCB with an 8,192 channel ADC. The digitalized output was then saved using the MAESTRO-32 software from ORTEC. The resulting neutron spectrum (Figure 8) shows the neutron response of the sample.

The response of the glass was measured for an irradiation period of 3,600 sec, after a 600 sec background acquisition was taken. The detection and irradiation system mentioned above was calibrated using a GS-20 glass sample as a reference. The resulting light output for the Ce:LBO system, obtained by summing all of the counts under the peak, was 1.33 x 10^{3} photons/neutron event. The spectrum shown in Figure 8 is in good agreement with that put forth by Ishi *et al.*[10]

Conclusions

The result obtained from the experiments demonstrated that glass samples, containing 0.5 wt percent CeO$_2$ and 17 wt percent boric acid, were successfully synthesized. The glass was a highly amorphous, transparent, polymeric lithium borate glass. The material was doped with Ce(III) by way of reducing Ce(IV) with excess boric acid at high temperatures, resulting in the development of lithium borate glass doped with Ce(III) without the use of a reducing atmosphere. The bonding mechanisms, namely the trigonal boron species formed six-membered rings that were tethered at the center by a single tetragonal boron species, was demonstrated. Elemental composition of the material was identified as having boron to lithium ratio of 1:2.21. The experimental data shows that maximum light output occurs at 360 nm, with high optical clarity from 330 nm to 800 nm, and approximately 35 percent absorption in the fluorescent region. Lastly, the CLSM work revealed that the samples were highly homogenous, indicating that the fission products produced in the matrix have a high likelihood of interacting with the scintillation centers. Upon, neutron irradiation, the sample was shown to detect neutrons and had a light output of 1.33 x 10^{3} photon/neutron.

Future Work

Future work with this material would be subject this material to further irradiations by thermal neutrons and gamma-rays for the purpose of radio-luminescence studies.

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Keywords

Scintillator, lithium borate, neutron detector, amorphous, cerium

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Verification Challenges and Opportunities

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Abstract

In July 2014, the Nuclear Threat Initiative (NTI) released *Innovating Verification: New Tools & New Actors to Reduce Nuclear Risks*—a four-report series that outlines the recommendations from NTI's Verification Pilot Project, which involved more than forty technical and policy experts from around the world. The two-year project was undertaken in collaboration with senior leaders from the U.S. Departments of Defense, Energy, and State as well as the governments of Norway, Sweden, and the United Kingdom. The reports focus on key verification challenges and include recommendations governments around the world can undertake to strengthen nuclear security and nonproliferation efforts and enable future warhead reductions. As the security environment continues to change, further cooperation in this area can generate more robust scientific and technical engagement, provide stability over time, and ultimately enable progress on critical threat reduction measures.

Introduction

Verification and monitoring activities are implemented around the world every day for commitments related to nuclear and chemical weapons, nuclear material, and other military activities. Inspectors use an extensive toolkit of instruments, techniques, and methods—including data exchanges, on-site inspections, tags and seals, containment and surveillance equipment, and environmental sampling—to verify compliance with a range of bilateral and multilateral agreements. The International Atomic Energy Agency (IAEA), tasked with detecting the misuse of nuclear material or technology, dispatches international teams of safeguards inspectors to collect data at more than 1,200 facilities worldwide. Experts from the Organization for the Prohibition of Chemical Weapons routinely inspect sites and recently oversaw the destruction of Syria's declared chemical weapons stockpile. And despite serious tensions between the U.S. and Russia, New START on-site inspections have continued. Such verification systems and methods are crucial to managing risks and mitigating threats, but gaps remain.

In the current security environment—deteriorating U.S.-Russian relations, tensions on the Korean Peninsula, questions about how a more assertive China could tilt the balance in the Asia Pacific, on-going hostility between Pakistan and India, a continued focus on Iran's nuclear program, and a persistent threat from non-state actors—the prospects for cooperation appear dim. But these challenges highlight the importance of verification and underscore its role in maintaining strategic stability and providing critical insight and predictability—especially during times of tension. Moreover, it is likely that going forward, states will need the ability to monitor and detect smaller items and quantities of nuclear material—tasks for which the current inventory of tools and technologies is inadequate.

Eventually, insight into the full scope of a state's nuclear weapons program may be required. Otherwise, there will be no assurance that warheads withdrawn from service and dismantled are not simply replaced or that a state's overall number of warheads does not increase. Verifying future nuclear reductions will be complex and challenging. All warheads, not only delivery vehicles, may eventually need to be counted and verified—a metric inspectors have not used in past agreements. Non-strategic nuclear forces will likely need to be accounted for and verified, a difficult challenge given that states with large non-strategic arsenals cannot agree on what exactly constitutes a non-strategic warhead. Warheads held in containers in storage facilities will also need to be taken into account. At the same time, the international community is anticipating the expansion of civilian nuclear power programs, possibly including sensitive enrichment and reprocessing capabilities, which could mean that all weapons-usable nuclear material will need to be continuously monitored and verified, a fundamentally different task from simply counting items. All of these changes will occur against a backdrop of quickly developing technologies and faster information flows that will demand more nimble government action.

Innovation in verification and monitoring capabilities is, therefore, a crucial mission for the international community. Verification approaches must evolve to account for new sources of information and technical methods, additional stakeholders, and issues such as cost and intrusiveness. No single approach by itself—onsite inspections, satellite imagery, data collection, or remote monitoring—will be enough. Rather, it will be the sum of many tools and techniques, both cooperative and unilateral, that will comprise an effective verification system. This will take time to develop, making it essential that states build on work done through key programs such as Cooperative Threat Reduction, the Trilateral Initiative, UK-Norway Initiative, and begin collaborative work now.

Given the current political environment and prospects for traditional arms control, this may seem like an inopportune time to undertake such an effort, but as former Senator and NTI Co-Chair and CEO Sam Nunn has argued:

> Given the serious challenges in today's global security environment and the lack of trust in the Euro-Atlantic region in particular, some may argue that this is not the right time to undertake cooperative development of verification approaches. My experience with Senator Richard Lugar underscores that cooperation in a time of low trust is more difficult but more essential. Twenty-three years ago, we proposed the Nunn-Lugar Cooperative Threat Reduction program, a joint U.S.-Russian effort to help Moscow and the former Soviet states secure weapons, materials, and know-how when the Cold War ended and the weapons and materials were scattered across many countries and time zones.
>
> It took a lot of effort and time to convince essential participants that securing and eliminating these materials was not a zero-sum game but a win–win for our nations and for the world. Despite a massive trust deficit after the Berlin Wall came down and at various periods since, Russian and U.S. defense workers, scientists, and members of the military over time learned to work together; for more than two decades, they verifiably destroyed thousands of nuclear weapons and delivery vehicles, secured and eliminated thousands of bombs' worth of nuclear material, and developed new areas for scientific and technical cooperation.

This philosophy has driven the Nuclear Threat Initiative's work on verification and monitoring for the past several years and was a key motivator behind NTI's Verification Pilot Project.

The Verification Pilot Project[1]

One of NTI's key areas of focus has been to renew international thinking and innovation on stringent monitoring and verification mechanisms, not only for a world without nuclear weapons, but for near-term policy priorities that are stalled and need a forward path. In 2010, NTI published a study, *Cultivating Confidence: Verification, Monitoring, and Enforcement for a World Free of Nuclear Weapons*, which explored the technical, political, and diplomatic challenges in this endeavor. The book outlined long-term issues that states need to address to ensure that nuclear weapons reductions can proceed safely and transparently.

In 2012, NTI created the Verification Pilot Project to deepen the analysis of issues that *Cultivating Confidence* explored. In partnership with senior leaders from the U.S. Departments of Defense, Energy, and State, as well as from the United Kingdom, Norway, and Sweden, the project sought to build knowledge and strengthen capacity for international verification efforts and future arms reductions goals, to build confidence between states with and without nuclear weapons, and to develop roadmaps for both technical and policy challenges that could be barriers to future progress.

The project tackled a set of issues, scoped with input from senior policy leaders and technical experts, that could help develop the foundations necessary to meet key arms control, nuclear non-proliferation, and nuclear security challenges. For example:

- There is no mechanism in place for tracking individual warheads or eventually accounting for all weapons-usable nuclear material.
- Advancements in big data and information analysis technologies could shed light on key activities and developments, but these tools are untested and not yet tailored to verification and monitoring tasks.
- Key players are excluded from some verification arrangements or, in some cases, do not yet have the necessary expertise to participate.

These challenges set the foundation for the Verification Pilot Project's three expert working groups, which included more than forty technical and policy experts from a dozen countries. The working groups met several times, both individually and collectively, and produced the following reports:

1. ***Verifying Baseline Declarations of Nuclear Warheads and Materials*** analyzes how states might prepare and eventually verify baseline declarations without compromising sensitive information and how such a process could build international technical capacity and trust over time.
2. ***Redefining Societal Verification*** explores how advancements in information technologies, big data, social media analytics, and commercial satellite imagery could supplement existing verification efforts by governments and increase contributions from outside experts.
3. ***Building Global Capacity*** considers the value of expanded participation in the verification of nuclear arms reductions and how this participation can increase confidence in nuclear threat reduction efforts among all states. The group also explored ways to build greater international capacity for verification and transparency so that interested countries would be prepared to actively participate in these efforts.

Common Themes

Despite the diverse nature of the working groups' subject matter and participants' backgrounds, some common themes emerged throughout the project. These findings can serve as a foundation for future verification approaches and offer an outline for how the international community can begin to prepare for both near-term and long-term verification challenges.

1. **The international community must work to build and sustain a global cadre of verification experts.** Despite decades of nuclear verification activities, primarily between the United States and Russia, the global expert base is limited. Years of inattention and underfunding has set back disciplines relevant to verification and monitoring. This deficiency is a crucial issue in the United States and Russia, and capacity is even less developed in other states. More experts—from states with and without nuclear weapons—should join international verification efforts to make them more effective and build confidence. To do this, all states must identify core competencies, build a cadre of experts, and seek to develop and participate in international verification efforts.
2. **Collaborative work on verification should start now.** There is a lack of urgency in advancing monitoring and verification policy and technical research. However, political change can happen quickly—even unexpectedly—and bold steps could be hindered if verification capacity lags behind policy appetites. New and proven verification tools and approaches can empower decision-makers to press for action if they are confident that nuclear reductions can be successfully implemented, but these instruments take time to develop. Efforts to preserve historical records, organize internal agencies and departments to successfully manage verification processes, and jointly developing equipment for key monitoring tasks should be prioritized.
3. **Future research and development should cross disciplines, communities, and nations.** Effective verification approaches require a diverse set of expertise and perspectives. Currently, excessive national, disciplinary, or institutional stove-piping hinder verification efforts and undermine even well-intended efforts to build capacity. For too long, verification and monitoring tasks have been seen as so unique and sensitive that experts have been isolated, thereby generating distrust and at times stifling innovation. With appropriate regard for the protection of sensitive information, deliberate efforts to cross-fertilize—even outside the nuclear weapons arena—can lead to new solutions to difficult verification problems.
4. **A new framework is needed for sensitive information.** Information about nuclear weapons can be extremely sensitive. But it may prove valuable to reassess why a particular piece of information is considered classified or why access to a particular site is prohibited. In some cases, past decisions may be reinforced; in other cases, conclusions might change. Ten years ago, it would have been inconceivable that the United States and Russia would exchange global positioning system coordinates of nuclear delivery vehicles, but both sides determined that the interests of their countries were better served by sharing that information than by keeping it secret. A framework that considers the broader benefits of sharing certain information, in addition to any risks, will be crucial to making progress on even harder challenges.
5. **No single verification approach is enough.** Only by layering verification tools and approaches and by rationally combining them can states build confidence in the overall system. No single method is completely effective, and it is unrealistic to set this as a goal. Instead, the goal should be to build a robust system of measures in which cheating is likely to be either detected or deterred. Verification instruments and techniques should be thought of together as a system that can increase confidence in the overall results.

6. **Verification is an area where all can contribute.** Not all states have equal roles, equal access to information, or equal interest in participating in verification efforts. However, all states have something to gain by expanding the circle of experts who can quantifiably verify the inventory and irreversibility of nuclear arms reductions. States with nuclear weapons can show the processes by which reductions can verifiably take place, including the pace of dismantlement and ultimate disposition of the components. For states without nuclear weapons, a better understanding of and participation in the verification process can build confidence that states with nuclear weapons are meeting their commitments because their actions can be demonstrated rather than just asserted. For states in regions of tension, verification may help reduce uncertainties that undermine trust and lead to potentially dangerous decisions about nuclear weapons, technologies, or other destabilizing activities.

Working Group Findings and Recommendations

Verifying Baseline Declarations of Nuclear Warheads and Materials

NTI charged a group of nearly twenty technical and policy experts with examining the issues and methods associated with verifying baseline declarations of nuclear warheads and weapons-usable materials. The working group was divided into two subgroups: one analyzed warheads; the other studied nuclear materials.

As states move to lower numbers of nuclear weapons and need the ability to detect and monitor smaller items and quantities of nuclear material, verification will become a more complex challenge. The full lifecycle—from material inventories, warhead assembly, and deployment to storage, dismantlement, and disposition—may eventually have to be monitored and verified, a task that will be extremely difficult if inspectors do not have detailed records of a state's total warhead and weapons-usable material inventory. Such records will take time to develop, and there are currently no agreed mechanisms for recording, sharing, or verifying this information. Verifiable baseline declarations will be essential to filling this gap.

A baseline declaration is defined as an initial statement of the number or quantity of accountable items or materials—perhaps specified by parameters such as type or category—against which other information may be compared and future progress may be measured. Without a clear understanding of warhead and nuclear material inventories, it will be nearly impossible to confirm that there are no hidden items or clandestine activities, making additional arsenal reductions extremely difficult. By declaring and verifying baseline inventories of warheads and weapons-usable nuclear materials, a state can assuage other states' real and perceived national security concerns. This will be an essential first step in maintaining the confidence of all states in a long-term arms reduction process.

Joint Recommendations

- *Prioritize and expand multilateral technical engagements.* It can take years to qualify tools for inspections. States that have collaborated in developing and testing specific methods for high-security authentication, unique identification, and continuity of knowledge become intimately familiar with their design and application. Such familiarity can foster cooperation and may make states more likely to include these systems in future agreements.
- *Prioritize verification research and dialogue.* Collaboration on verification methods and techniques should be complemented by a sustained dialogue among government officials and international experts on practical and technical approaches to baseline declarations and verification arrangements. Topics for engagement could include:
  - Declaration content and format
  - What information states are prepared to make public, exchange with other states confidentially, or share with particular states
  - What information should be preserved through nuclear archeology programs to facilitate future verification, such as historical information on material flows and facility information
  - What is needed for effective verification, what existing measures can achieve, what complementary regimes and activities can contribute, what obstacles may arise, and what areas require further development
  - Who would verify baseline declarations, what areas might be priorities for verification, and how verification could be phased in to address these top priorities
  - How an integrated system for verification and evaluation could be developed, and how states can mitigate the risks posed by the retention or clandestine production of warheads or materials.

Review national classification standards and information. For future verification systems to be as effective as possible, parties will need to deal with differences in national classification standards. This should begin with each state reviewing internally what it currently considers classified information, and whether certain information can be declassified or shared in some form with other governments in the context of deep reduction and verification requirements.

Warhead Subgroup Recommendations

- *Discuss warhead environments and safety and security requirements as a part of the P5 dialogue on verification*: China, France, Russia, the United Kingdom, and the United States need to discuss and share information about the general nature of the safety and security concerns and procedures that characterize their respective weapons environments and which would bound the activities allowable in a baseline verification process. Such information sharing would constitute a type of confidence-building measure that would help strengthen the basis for multilateral arms control in the future.
- *Initiate an international technical assessment on warhead containers*: The ability to accurately measure a containerized warhead or component, without revealing sensitive information, is essential. A container study would give states a better understanding of container effects and help determine if standardized containers or standardized container design principles could simplify the confirmation process.
- *Launch a joint study on the applicability of IAEA technologies for warhead environments*: Currently, the IAEA employs a wide variety of safeguards tools and techniques, including tags, seals, unattended monitoring, and environmental sampling. An international team of experts should explore whether or not these technologies would be useful for verification and could be used in a warhead environment.
- *Prioritize research on authenticating information barriers*: The United States, Russia, the United Kingdom, and others have had limited but important success in developing and demonstrating measurement systems with integrated information barriers that protect sensitive information. However, to date, it has not proved possible for these foreign specialists to authenticate the inspection system. Creative solutions and suggestions for improvement should be solicited from information technology experts and could be crowd-sourced as well.
- *Strengthen independent peer review and vulnerability assessments on ongoing research and development efforts*: As promising technologies advance through the development process, programs need to involve additional independent, scientific certification and vulnerability assessment teams. A more extensive peer-review process would bolster research and development (R&D) outcomes and acceptance, as would the detailed publication of research results.

Material Subgroup Recommendations

- *Share best practices*: Some states have valuable experience that, if shared, could enable other states to make unilateral declarations, reduce barriers to formal baseline declaration arrangements, and move the development of verification methods forward. U.S. and U.K. experts should engage with their counterparts in other states with nuclear weapons to share their experience in assembling information on their historic plutonium and HEU production and use. It would also be helpful if South Africa were prepared to develop a report on its experience of having the equivalent of a baseline declaration verified and if the IAEA, in consultation with South Africa, reported on its perspective on the lessons from the South African experience.
- *Pursue joint R&D on nuclear archeology methods*: Funding and expertise for collaborative R&D of nuclear archeology methods for different reactor types and uranium enrichment technologies should be prioritized. Methods for graphite-moderated plutonium production reactors are well established, but further work is needed to develop approaches for heavy water reactors as well as gaseous diffusion and centrifuge enrichment plants.
- *Develop verification approaches for naval fuel*: Due to national security and proprietary concerns, HEU in the naval sector is a particularly vexing verification challenge. States that use HEU in naval fuel should establish a cooperative dialogue to develop verification approaches to confirm, without compromising sensitive information, that none of the material designated for naval use is being used to produce warheads, in violation of agreements.
- *Transfer weapons-usable materials that are excess to military requirements to civil programs under IAEA safeguards*: Where weapons-usable materials have been sanitized and are excess to military requirements, as with materials released through warhead dismantlement or stocks

that are no longer needed, the material should be either verifiably disposed of and rendered practicably irrecoverable or transferred to civil programs and placed under IAEA safeguards. A longer-term objective should be for the IAEA to apply active safeguards to all weapons-usable materials in civil programs in all states.

Redefining Societal Verification

NTI convened a group of multi-disciplinary experts to examine the potential for new technologies to supplement future arms control verification and monitoring techniques.

Information and communication technologies (ICT) have reshaped how countries, corporations, and private citizens share, collect, and analyze information. As global communication technologies have increased, so too has the amount of publicly generated data. The big data phenomenon has led to groundbreaking innovations in emergency response, humanitarian relief, disease control, and commercial marketing and sparked interest in the nuclear arms control and nonproliferation domains.

With the vast amount of information available today, external analysis will continue to improve, whether or not governments leverage new media themselves or embrace the potential contribution of outside experts to treaty verification efforts. Accessible technical capacity, like smartphones with wireless communications connectivity, built-in sensors and geolocation capabilities, and data storage and processing capability continues to improve and expand. These capabilities offer knowledgeable citizens powerful tools to collect and share information. Through societal verification, states can leverage new technologies and publicly available data to supplement national technical means (NTM) and other traditional verification methods.

The working group redefined societal verification as a process by which states or international organizations can use information generated and communicated by individuals or expert communities for arms control or nonproliferation treaty verification. The concept of societal verification, in some form or another, is not new, but ideas about how societal verification might contribute to state efforts have evolved in recent years. Even though state systems have not yet caught up to the promise of societal verification, in a world of abundant data and perpetual connectivity, the technical has joined the conceptual, making some level of societal verification a real possibility in a way that was not previously achievable.

Recommendations

- *Governments need to build a foundation for societal verification within the current arms control policy leadership. They should develop policies, diplomatic guidance, and bureaucratic structures to evaluate and integrate societal verification data in treaty verification. To take advantage of new tools and techniques, governments should*:
  - Map out an effective process for societal verification data integration and program management to support future verification systems and begin to address questions such as:
    - Which agency has the lead?
    - How will the effort intersect with the private sector, the intelligence community, and other potential contributors?
    - How can conclusions be validated using inputs from traditional verification tools?
  - Begin international consultations on how future arms reduction agreements may acknowledge and develop rules for the use of societal verification data.
  - Explore the possibility of experimenting with cooperative societal verification measures with allies to provide empirical data and lessons for how societal verification may be implemented in the future.
  - Start developing rules related to the legal, ethical, and privacy concerns surrounding use of citizen-generated information.
- *The international technology and policy community should collaborate to develop a technology needs assessment/research and development roadmap to build capacity within government systems. Areas of exploration might include the following*:
  - Natural language processing of foreign languages as well as informal and unstructured language, such as slang and terms of art.
  - Challenges posed by real-time processing of data versus queries of stored information.
  - Identifying key or leading indicators of treaty-proscribed activities around which appropriate queries can be developed.
  - Identifying attempts to censor or spoof data, especially where there is knowledge that information is being analyzed.
  - Aggregating and integrating signals from multiple sources across platforms and data types to increase confidence.

- *Governments, in cooperation with outside expert communities, should establish channels to elicit the input of outside analysts to help build approaches for societal verification as follows*:
    - Assess capacity and fill gaps to enable contributions by outside experts to societal verification efforts of governments.
    - Develop methods and mechanisms to educate expert communities outside the government on existing national verification efforts.
    - Develop ways to identify, connect, organize, guide, assist, and reward experts, recognizing that validation and anonymity are not always compatible.
    - Create paths to solicit input in a timely manner on potential verification challenges.
    - Encourage discussions and cross-checking among external experts, facilitating a two-way information flow to build valuable capacity outside government.

Building Global Capacity

NTI's working group on building global capacity discussed opportunities to expand the number of states involved in future verification activities. The group consisted of experts from six countries, including both states with and without nuclear weapons.

States with nuclear weapons will be less likely to pursue deep reductions if more states acquire nuclear weapons or latent nuclear weapons capability because of the spread of uranium enrichment and plutonium reprocessing technologies. Non–nuclear weapon states (NNWS) thus have both an individual interest and a collective responsibility to ensure that the goals of the treaty are met, including through constraints on sensitive fuel cycle facilities to preclude the development of nuclear weapons programs. NNWS will be less likely to accept such constraints if they perceive that nuclear weapon states (NWS) are not taking their disarmament commitments seriously or, worse, are misleading the international community about their nuclear weapons reductions. All states have compelling reasons to hold the others accountable for their actions. For NWS, demonstrating compliance builds trust; for NNWS, being able to participate in some measure of verification is the most effective form of reassurance and allows them to appreciate the challenges NWS face in reducing their nuclear stockpiles. Further, states not party to the NPT have a stake in helping to develop and engage in verification of nuclear commitments, especially those that might relate to regional arrangements.

Verifying nuclear arms reductions is a highly complex and sensitive undertaking. Historically, states with nuclear weapons have tended to resist engagement with states without nuclear weapons due to concerns that sensitive information may be revealed in the process. Practical examples and joint projects help demonstrate that there is a great deal states without nuclear weapons can be involved with while successfully managing proliferation risks.

While reducing nuclear risks and ensuring that arms reduction commitments are being fulfilled are goals shared by all, individual countries' level of interest in arms control verification and technical capacity to participate in verification activities vary greatly and will change over time.

There are significant gaps at the national level in most countries when it comes to mobilizing and organizing the relevant technical and administrative skills, yet it might surprise some to realize that many of these skills already exist in most countries. For example, technologies used for nuclear medicine and remote sensing and geospatial data software can be applied to verification missions. A systematic process to define gaps and fill them—to build capacity—would allow new states to join verification and monitoring efforts when they are ready. There is evidence from past experimental projects that some states without nuclear weapons would show immediate interest in a focused dialogue on verification, if given the opportunity. For many other states, the consensus judgment of other, trusted countries would provide sufficient reassurance. Capacity building is not, however, a synonym for technical training; existing skills need to be brought together in a framework dedicated to arms control. This process will take years, so interested parties should start now.

Recommendations for States with Nuclear Weapons

- *Determine national inspection sensitivities*: If states with nuclear weapons intend to work with states without nuclear weapons, they need to begin by ascertaining what knowledge, methodologies, and technologies can be shared without revealing sensitive information that could contribute to proliferation.
- *Establish, re-establish, or expand government programs dedicated to verification*: Dedicated government programs are required to devote the necessary resources to the task and ensure efforts are sustainable over the long haul.

- *Consider sharing information on risk management associated with inspections*: States with nuclear weapons can learn a great deal from each other about how inspections at sensitive facilities are managed. Sharing lessons learned will be useful and, eventually, will facilitate engagement with states without nuclear weapons.
- *Preserve program records, supporting data, knowledge, and institutional memory*: As the experience of South Africa, described in this report, shows, better documentation can increase the level of confidence in verification findings and reduce workloads. Maintaining clear and consistent records makes demonstrating compliance much easier.

Recommendations for States without Nuclear Weapons

- *Determine what they want to achieve from engagement in a verification process*: States without nuclear weapons need to develop a basic understanding of the benefits and limitations of verification to determine the value of engaging and the return that can be expected on that investment.
- *Promote academic programs that build verification skill sets*: Promoting specific programs with verification applications will help interested countries build capacity in functional areas.
- *Establish a government program dedicated to verification and identify a lead authority*: Just as in states with nuclear weapons, dedicated government programs in states without nuclear weapons are required to devote the necessary resources to the task and ensure efforts are sustainable over the long haul.

Collective Recommendations

- *Explore regional approaches to capacity building*: Different countries possess different skills that can be found in the government, military, academic, and private sectors. These should be brought together. Useful first steps include identifying regional champions for the verification mission and establishing a group of interested parties that will conduct joint outreach on verification issues through activities such as dedicated workshops.
- *Conduct joint development, testing, and certification of verification tools and nuclear forensics*: Joint development is an extremely effective way to build both knowledge and trust among partners.
- *Share experiences lessons learned from existing verification activities*: Experiences should not be limited to the nuclear realm and could include regimes such as the Chemical Weapons Convention.
- *Design and conduct a mock inspector training course*: This course could be modeled on the New Strategic Arms Reduction Treaty (New START) inspection regime, open to participation from states with and without nuclear weapons, and designed to share lessons learned from decades of U.S. and Russian experience.

Conclusion

It is time for the international community to fundamentally rethink the way it designs, develops, and implements arms control verification approaches. An international initiative pursued with creativity, broad participation from states with and without nuclear weapons, and a sense of urgency and common purpose could make a significant contribution, regardless of the near-term prospects for traditional arms control.

Going forward, an international partnership designed to systematically assess and develop solutions for monitoring and verification challenges across the lifecycle—from material production and control, warhead assembly, and deployment to storage, dismantlement, and disposition would build on the recommendations from the Verification Pilot Project and other efforts. While the P5 dialogue on verification and other ad hoc initiatives have made important contributions, a broader international Track 1.5 effort that was designed to share costs, identify joint priorities, build capacity, and provide a platform for dialogue and collaborative research and development could improve trust and transparency and enable even greater participation in future threat reduction efforts. Such an effort would also give parties an opportunity to better understand different safety and security requirements for certain environments, continue discussions on how to protect sensitive information and manage access, and explore new methods for data authentication, integration and flow across the lifecycle.

If critical research and development on future monitoring and verification capabilities is postponed, new arms reduction efforts will stall, and strategic stability could be at risk. Active steps on verification can strengthen nonproliferation and nuclear security in the near term and catalyze new arms reduction commitments in the longer term. If we are to build the trust required for a safer world, verification efforts and improvements must be a top priority. With the commitment of governments and the engagement of a growing cadre of professionals, verification can be the catalyst that inspires and empowers countries to make nuclear reductions and move toward a more secure world.

Endnotes

1. The results of this project, released in July 2014, can be accessed at the NTI website.

Proliferation Resistance Analysis and Evaluation Tool for Observed Risk (PRAETOR)—Methodology Development

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Abstract

A computer code, named PRAETOR (Proliferation Resistance Analysis and Evaluation Tool for Observed Risk), has been developed to aid in comparing the proliferation resistance (PR) of nuclear installations. The well-established decision analysis methodology called Multi-Attribute Utility Analysis (MAUA) is the backbone of the code and the code is developed using the Fortran 90 programing language. The PRAETOR code employs attributes, which considers both intrinsic and extrinsic measures at a nuclear installation that inhibit special nuclear material (SNM) proliferation. Currently, PRAETOR uses sixty-three attribute inputs to capture the PR characteristics of the SNM and the nuclear installation being analyzed. The PRAETOR code derives a single metric for PR performance comparison by appropriately folding the sixty-three inputs using their respective weights (relative importance) and the MAUA methodology. Two nuclear material diversion scenarios for a nuclear fuel cycle installation are shown to give reasonable insights into the facility PR characteristic for decision making.

Introduction

The vulnerability of special nuclear materials (SNM) to diversion from peaceful to military uses, such as nuclear weapons and radiological dispersion devices, is a major issue in the current period of the nuclear energy renaissance. Quantitative assessment of proliferation resistance (PR) for a nuclear fuel cycle (NFC) remains a formidable task. A suitable methodology for the PR assessment of a nuclear facility is valuable for the purpose of presenting concise and accurate data to the installation designers, decision makers, and the public. There have been sizable and diverse efforts to develop both qualitative as well as quantitative methodologies for PR assessment for decades.[1,2] However, the absence of one, or a few, widely established standard PR methodologies complicates selecting a suitable one for creating accepted benchmarks.

PR is defined as that characteristic of a nuclear energy system that impedes (a) the diversion or undeclared production of nuclear material or (b) misuse of technology by states in order to acquire nuclear weapons or other nuclear explosive devices.[3] Two important measures of PR are *the intrinsic* features of the SNM and *the extrinsic* barriers at the nuclear installation. The intrinsic features result from the technical design of the nuclear energy systems and the extrinsic measures are those that result from the implementation of a states' undertakings related to nuclear nonproliferation.

Research efforts began in the early 2000s at Texas A&M University (TAMU) to develop a methodology for the PR assessment of NFC technologies. There were collaborators in these early efforts from the University of Texas (TU-Austin), BWXT-Pantex (Amarillo, Texas), Oak Ridge National Laboratory (ORNL), Sandia National Laboratories (SNL), and AREVA.[4-6] This work concentrated on PR assessments based on the Multi-Attribute Utility Analysis (MAUA) theory.[7-10] A journal publication based on this work describes the PR analysis of single nuclear process systems such as a pressurized water reactor (PWR), a CANDU reactor, UREX and PUREX reprocessing plants, and spent fuel storage facility.[11] This journal publication also discusses the PR values obtained for the SNM present at different installations of a once-through PWR fuel cycle and for a closed PWR fuel cycle using UREX separations and an accelerator driven system (ADS) burner.

Further, a report based on this work laid down the foundations for carrying out a MAUA based PR assessment.[12] This report also presents the results of two of the PR assessment example scenarios carried out. Both of these publications employed the additive form of MAUA function. Subsequently, studies at TAMU were made using the multiplicative MAUA function for the PR assessments.[13,14] Based on the experience gained from the aforementioned research efforts on PR assessments using MAUA, a computer code, named PRAE-

TOR (Proliferation Resistance Analysis and Evaluation Tool for Observed Risk), was developed to aid in comparing the PR of nuclear installations. PR methodologies, MAUA theory, developmental aspects of the PRAETOR code, and example PR assessments carried out are described in the following sections.

Overview of Proliferation Resistance Methods and Risk

Contemporary PR analysis falls within the two main categories of Barrier or Pathway methods. In Barrier PR methods technical knowledge, resources, and material attributes are assessed for a specific, or group of, proliferation pathways. The Pathway PR methods emphasize PR trade-offs for different proliferation pathway arrangements leading to nuclear weapon attainment. A short overview of PR assessment tools using Barrier and Pathway methodologies is presented in this section to clarify their different relative strengths and weaknesses.[15]

Proliferation Resistance: Barrier Methodologies

PR tools using the Barrier approach possess several advantages from a development standpoint. Relative to Pathway methods, Barrier analysis can rely on attributes such as physical and material parameters that are well understood and can be quantified. Barrier method code and tool operations tend to be more straightforward for the end user.

Pathway tuning for a particular Barrier method is a weakness for PR assessments. If the assessed major pathway facilities diverge significantly from the underlying base Barrier pathway the PR value reliability drops. For instance, a Barrier method might be based on assessing transformation facilities, such as uranium enrichment and plutonium separation plants, with higher extrinsic material protection or detection aspects. The transformation tuned Barrier code would be less accurate when analyzing the PR of conversion or fuel fabrication facilities emphasizing intrinsic safeguards for material accountancy.

Minimal proliferator intelligence to overcome challenges is incorporated in Barrier methods. Acquiring dual use advanced technology components abroad by a proliferator allows it to surmount domestic technical constraints. Concurrently pursuing multiple proliferation routes potentially permits information sharing between pathways. Thus, two seemingly independent routes might have lower than expected PR protection values.

The Technological Opportunities to increase the Proliferation resistance of global civilian nuclear power Systems (TOPS) program initiated most Barrier methods.[16] With TOPS a framework was developed encompassing a methodology and attributes evaluating full civilian NFCs. The 2003 National Nuclear Security Administration's (NNSA) Nonproliferation Assessment Methodology (NPAM) provided guidelines for integrated PR attribute and scenarios. The 2003 NPAM roughly outlined the earlier Barrier and Pathway analysis categories.[17]

The Generation-IV International Forum Proliferation Resistance and Physical Protection (PRPP) and AREVA designed Simplified Approach for Proliferation Resistance Assessment (SAPRA) are successive Barrier methods.[18-21] The PRPP process flexibly handles in-depth cataloging of proliferation barriers for a range of NFC facilities. With PRPP an adversary threat characterization is performed to bound the likely potential proliferator capabilities. The PRPP Barrier method can therefore consider the pathways more attractive to certain proliferators based on their skill level. SAPRA breaks proliferation down into stages: (1) diversion of nuclear material, (2) nuclear material transportation to another site, (3) material transformation into weapon applicable form, and (4) material weaponization through physics package creation.[22] SAPRA takes additional PR outcome modifiers into account through country technology summaries.

The International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) mission included a need to develop the tools to analyze the role and structure of Innovative Nuclear Energy Systems (INS) required to meet sustainable energy demands … and to develop the methodology for assessing INS.[23,24] INPRO was modernized to better accommodate Pathway assessments through the 2008 Proliferation Resistance Acquisition/Diversion Pathway Analysis (PRADA) project. PRADA is designed to handle three levels encompassing: the State, Innovative Nuclear Energy Systems (INES), and the NFC facility.[24] PRADA considers the combined impact of multiple PR barriers; and, it also recognizes the need to engage nuclear experts in the technology, PR, and safeguards fields to include their input for proliferation risk analysis.[25]

The North Carolina State University Fuzzy Logic Barrier (FLB) Method is another Barrier method.[26] Fuzzy Logic ranks qualitative fuel cycle attributes through quantitative weighting. Physics fidelity stems from integrated ORIGEN-S inputs and outputs incorporated into the FLB to obtain isotopic data for each fuel cycle stage in PR determinations.

Proliferation Resistance: Pathway Methodologies

The challenge from several potential proliferator pathways leading to nuclear weapons is considered with PR Pathway analysis methods. Pathway analysis allows a proliferator to gain knowledge and experience from even failed proliferation routes. Tradeoffs are ever present between pathways with latent deterrent or diversion NFC objectives. The inclusion of the choice an intelligent proliferator can make in this Pathway analysis adds realism from a predictive standpoint.

Complex Pathway scenarios with large data requirements can have more development and deployment risks. The range of proliferator choices in Pathway models creates uncertainty in the resulting PR values; and, therefore strong verification and validation studies, including benchmark testing, are required for Pathway tools. Establishment of respected and accepted Pathway tools also requires significant investments from programming and data acquisitions perspectives.

The Risk-Informed Probabilistic Analysis (RIPA) methodology was one of the first Pathway tools developed shortly after TOPS.[6] Sandia National Laboratories (SNL) developed RIPA using deductive reasoning along the lines of fault trees for predicting proliferator nuclear weapon pathway activities. A major RIPA advantage was proliferator cost and time computations for handling proliferation goal variations.[27] A Markov model for evaluations using the PRPP methodology was also produced at Brookhaven National Laboratory (BNL) to analyze proliferator pathways for a particular scenario. The BNL PRPP Markov add-on takes into account possible pathway detection, transition, and failure rates.

Bayesian networks are used in a recent Pathway model developed by Corey Freeman at Texas A&M University (TAMU), and later extended by Michael Mella.[28,29] TAMU's Pathway tool used Netica Bayesian software models to look at the adversary decision making to increase its overall success probability through intelligent information sharing amongst proliferation options. The TAMU Bayesian Pathway methodology does need substantial pathway and adversary input data. In the absence of adversary detailed information, proliferation pursuit strategy, and likely progression rates the corresponding model accuracy may be an issue.

Incorporating Risk into Proliferation Resistance

Identifying proliferation pathway success parameters matters; since, the responsible stakeholder must know how to rate the risk from an adversary's indigenous and foreign acquired knowledge, technology, and skills.[30] With the goal of employing basic calculations where possible, the risk equation for nuclear proliferation is described for any i-th risk:

$$R_i = P_{A,i} * P_{S,i} * C_i \qquad (1)$$

R_i is the risk of nuclear proliferation from a particular adversary set of pathways. The $P_{A,i}$ value is the probability of the adversary pursuing a certain proliferation action pathway. The probability of the adversary succeeding along the i-th pathway is $P_{S,i}$. Lastly, C_i is the consequence of adversary proliferation success.

In Equation 1, PRAETOR is focused on answering the $P_{S,i}$ aspect based on the observed risks for a particular proliferation pathway. We assess the observed risk as opposed to the perceived risk. The perceived risk is the risk from the perspective of the analyst. We cannot *a priori* predict the analyst's perspective of the risk; and, therefore we only assess that risk which could be statistically observed.

The C_i term does not consider the likelihood of successful nuclear weapon deterrence or terrorist activities upon nuclear material acquisition. Rather, it considers the risk associated with an adversary obtaining a nuclear device from a particular pathway relative to other acquisition pathways. The consequence for an adversary detonating a nuclear weapon on its territory is essentially incredibly high. However, generally low $P_{S,i}$ values, coupled with high costs yielding small $P_{A,i}$ rates, due to adversary deterrence and resource frugality, leads to an overall low R_i; thus, successful nuclear weapon proliferation with a deliverable weapon is a low occurrence risk event, but one with enormous consequences were it to occur.

MAUA Theory[7-9, 11,13,14]

In general, the MAUA methodology consists of compiling multiple factors into a single metric to facilitate easy decision making; and, MAUA has the ability to incorporate complex and inter-related components in a decision. For instance, each factor in the PR analysis has impacts on risks, resources, timelines, and/or levels of effort associated with the acquisition of a significant quantity (SQ) of SNM, a SQ is defined as the approximate amount of SNM for which the possibility of manufacturing a nuclear explosive device cannot be excluded.[31]

The initial task of MAUA is to form a set of individual attributes, (xi), that can best describe the system under consideration. The attribute values assigned by the analyst (or user) are mapped to a utility value (ui) between 0 and 1 using appropriate objective functions, commonly referred to as utility functions. The higher the utility value, the higher the PR of the system. Each of these utility values should have a user defined weight (wi) to reflect their relative importance. The MAUA theory provides a method to fold these multiple utility values and their respective weights into a single PR value, which then can be used to compare the merits and demerits of different systems.[8,9]

The various steps involved in the MAUA assessment are:

- Define an overall utility function U(x_1, x_2,.....x_i) to represent the value for a range of attribute values x_i;
- Define the single-attribute utility functions u_i (x_i) that contribute to this overall utility;
- Define a set of attributes, {x_i}, that can be related to cost, time, material quality, or other characteristics deemed of value or utility.

It is important to assume preferential and utility independence of the chosen attributes, so that the MAUA theory relationships are valid. The general form of MAUA function is

$$\mathrm{U}(x_1, x_2 ... x_n) = \sum_{i=1}^{n} k_i u_i(x_i) + K \sum_{\substack{i=1 \\ j>i}}^{n} k_i k_j u_i(x_i) u_j$$

$$(x_j) + K^2 \sum_{\substack{i=1 \\ j>i \\ l>j}}^{n} k_i k_j k_l u_i(x_i) u_j(x_j) u_l(x_l) + ...$$

$$........ + K^2 k_1 k_2 ...... k_n u_1(x_1) u_2(x_2) ...... u_n(x_n)$$

where the functions u_i are utility functions for the individual attributes normalized to a scale from 0 to 1, the constants k_i are weighting factors {$0 < k_i \leq 1$} for each attribute which indicate an attribute's importance relative to the others, U is the overall utility value (single metric) obtained for the PR of the tier, and the constant K is a scaling parameter that is a solution to the following equation with the constraint that $K > -1$:

$$1 + K = \prod_{i=1}^{n} (1 + K k_i) \qquad (3)$$

When the sum of all individual weighting factors k_i is equal to unity, then the scaling parameter, $K = 0$ and Equation 2 reduces to the additive utility function given by:

$$\mathrm{U}(x_1, x_2 ... x_i) = \sum_{1}^{n} k_i u_i(x_i) \quad \text{(Additive functional form)} \qquad (4)$$

However, when the sum of the weighting factors $k_i \neq 1$, then $K \neq 0$ and we can multiply each side of Equation 2 by K, add one to each side and factor to obtain the multiplicative utility function given by:

$$1 + K\mathrm{U}(x_1, x_2 ... x_i) = \prod_{i}^{n} (1 + K k_i u_i(x_i)) \qquad (5)$$

$$\text{(Multiplicative functional form)}$$

The additive utility function works out to be a weighted average of all the individual attributes. Each metric has a utility value $u_i(x_i)$ between 0 and 1 and their weighting factors k_i are also between 0 and 1. In order for Equation 4 to yield a high value for PR [i.e., U(x_1, x_2, x_3 ... x_n) close to unity], most of the individual utilities $u_i(x_i)$ must have a high value. This is beneficial if the analyst's goal is to find a system that performs well against as many measures of PR as possible. However, this method also limits the influence of any one attribute to the value of its weight. This means that the method will not perform correctly in limiting cases. For example, one could consider uranium ore to be extremely proliferation resistant because it is one of the least concentrated forms of fissile material on Earth, but if the weighting factor for the metric mass/SQ (see the attributes list given in Table 1) is 0.1, then this single factor will only add 10 percent to the overall PR value of the uranium ore.

The multiplicative utility function works differently. Its result is still a PR value between 0 and 1, but it allows for extreme values to affect the result more heavily. In Equation 5, if any attributes' utility value $u_i(x_i)$ goes to unity, it will have a much greater influence on driving the overall PR value towards unity. This demonstrates more appropriate behavior in limiting cases. The drawback is that the equation is somewhat less sensitive to changes in intermediate values. However, it will still serve adequately in comparing two technology options against one another.

The PRAETOR code provides the user with the option to perform MAUA in its Additive as well as Multiplicative mode.[32] The conditions to perform the Multiplicative mode of MAUA are: (i) the sum of the weighting factors, k_i, must not be exactly 1.0. If this condition is not met, the scaling parameter, K = 0 and the utility function equation given by Equation 2 reduces to additive utility function given by Equation 4; (ii) the solution obtained from Equation 3 for the scaling parameter, K should satisfy $-1 < K < 0$; (iii) the weighting factors cannot each be equal to 1.0, and (iv) weighting factors should satisfy the criteria {$0 < k_i \leq 1$}. In the present version of the PRAETOR code, to

Table 1. List of attributes

Stage I. Diversion

Subgroup I.1: Material handling difficulty during diversion

1. mass per Significant Quantity (SQ)
2. volume per SQ
3. number of items per SQ
4. material form
5. radiation level in terms of dose
6. chemical reactivity
7. temperature of the source process
8. heat load of material

Subgroup I.2: Difficulty in evading detection, material accounting & control system

9. uncertainty in accountancy measurements
10. expected Vs. actual material unaccounted for (MUF)
11. frequency of measurements
12. amount of material available
13. probability of detection

Subgroup I.3: Difficulty of covertly making facility modification

14. is there space to make modifications?
15. number of people for modifications
16. whether remote handling tools required?
17. whether specialization tools required?
18. whether the process need to be halted?
19. risk of modification with respect to safety
20. risk of penetrating containment

Subgroup I.4: Difficulty of evading IAEA with covert facility modifications & process monitoring

21. probability of getting caught by IAEA accounting
22. probability of detection by process monitoring

Stage II. Transportation

Subgroup II.1: Material handling difficulty during transportation

23. mass per SQ
24. volume per SQ
25. material form
26. radiation level in terms of dose
27. heat load of material
28. chemical reactivity
29. immediate chemical toxicity
30. time averse chemical toxicity

Subgroup II.2: Difficulty of evading detection during transport

31. mass of material and transportation container

Stage II. Transportation Continued

32. volume of material and transportation container
33. heat load of material
34. shield thickness to reduce radiation
35. host country size
36. number of declared nuclear facilities
37. IAEA imagery analysis rate

Stage III. Transformation

Subgroup III.1: Facilities and equipment needed to process diverted materials

38. number of steps to metallic form
39. number of export controlled equipment
40. minimum electrical requirement

Subgroup III.2: Workforce required for transformation

41. number of unskilled workers required
42. number of skilled workers required
43. number of advanced degree workers
44. number of technical experts

Subgroup III.3: Difficulty of evading detection of transformation activities

45. is additional protocol in force?
46. long range environmental sampling rate
47. sensitivity of IAEA equipment
48. isotopic signatures
49. facility size
50. heat load of transformation process
51. sonic load
52. radiation load
53. volume of non-naturally occurring gases emitted
54. undiluted volume of liquid emission

Stage IV. Weaponization

Subgroup IV.1: Difficulty associated with design

55. spontaneous fission product rate
56. radiation exposure at one meter
57. heating rate of weapons material
58. whether ballistic assembly method can be used?
59. number of phases in phase diagram

Subgroup IV.2: Handling difficulty and skills for design

60. radiation level in terms of dose
61. chemical reactivity
62. radio-toxicity
63. knowledge and skill level for weapon type alternatives

meet the criteria set by the Multiplicative mode, the user supplied weighting factors, k_i, are re-normalized so that the sum of the weighting factors, k_i, is not equal to 1.

PRAETOR Code Development

The PRAETOR code performs MAUA in three tiers with different attributes to describe the system being analyzed for PR. At the lowest tier, tier 1 PRAETOR uses sixty-three input attributes, which will be defined for the remainder of the paper as inputs, to describe the system being analyzed for PR. The input attribute cover a wide range of technical and nuclear material intrinsic barriers along with the extrinsic barriers based on the host state commitment to implementing domestic and IAEA safeguards. The extrinsic barriers are based on user characterization of the host state, and hence potential proliferator, commitment to preventing proliferation. Further state proliferator characterization is not performed with PRAETOR, and neither are sub-state proliferators like terrorist or criminal organizations considered. The sixty-three metrics are arranged within eleven sub-group attributes for tier 1. The eleven sub-groups were developed in conjunction with SNL and so have been vetted along the lines of SAPRA.[12]

For tier 2, the eleven sub-groups form into the following four major stages based on SAPRA's diversion based proliferation breakdown: Diversion, Transportation, Transformation, and Weaponization.[12,13] The Diversion stage considers the removal of nuclear material at least originating at a declared nuclear facility. Material diversion can occur during the movement of material; however, the location during transit where the material is moved from official accounting to illicit channels is the Diversion stage location. The Transportation stage encompasses nuclear material movement from the site of diversion to a transformation facility to create weapons-usable material. With the Transportation stage, if the diversion occurs at a nuclear transformation facility then the associated Transportation PR would be low due to small movement detection opportunities.

The Transformation stage basis is the conversion of diverted material into a weapons-usable metallic configuration. If the proliferator acquired near or metallic weapons-usable nuclear material the Transformation stage PR value would approach 0. The Weaponization stage handles the design, casting, and machining of the transformed nuclear material into the needed form to yield a nuclear explosive device. A proliferator in the Weaponization stage is considered only for obtaining a nuclear device realistically designed to achieve at least a high multi-kiloton explosion. A terrorist desiring any appreciable nuclear yield is not considered. For the final level, tier 3, the four stages combine to define the Overall PR value.

The list of attributes and their classifications into stages (underlined), sub-groups (*italics*), and inputs are provided in Table 1. Attribute values aid in ascertaining conclusions regarding the possibility of material diversion at a given rate under certain conditions of risk. Several input attributes are important across different stage sub-groups. The utility values for the same input attributes are generally kept the same, or functionally related through scaling. Such actions are justified to ensure input attribute consistency when based on physical, intrinsic material properties such as material mass and radiation dose level.

These attributes are used in composite or in a weighted form to make a final assessment. Differences between MAUA analyses include the use of different weighting schemes, the use of various utility functions, and the selection of different attributes for inclusion. There are two kinds of weighting schemes used in this code for the individual attribute utility values as well as for the group utility values obtained at different tiers of the analysis. The first kind is a uniform weighting scheme (equal weights) and the second kind is based on a survey among nuclear non-proliferation experts.

At the first tier, the sixty-three input utility values are classified into eleven sub-groups. For each sub-group, MAUA is performed to derive a sub-group utility value by using the individual utility values and the respective weights assigned for the attributes belonging to the sub-group. These eleven sub-group utility values have user defined weights. At the second tier, MAUA gives utility values for the major four stages. These four major stages also have user defined weights. At the third tier, MAUA generates an overall utility value (PR) for the system analyzed. At any tier, the higher the utility value, the better the PR. The MAUA analysis results at each tier incorporating groups and sub-groups should aid the user in easily identifying the contributing factors to the PR. The three tier MAUA approach coded into PRAETOR is depicted in Figures 1 and 2.

The MAUA method does entail potentially substantial trade-offs in PR values. Input attributes important for characterizing the PR for one proliferation pathway might provide negligible PR for another pathway. For instance, the roles of radiation dose and heat lead in PR for plutonium acquisition are significantly more important than for impeding highly enriched uranium diversion. Rarely will PRAETOR return PR values below 0.1, or above 0.8. Inclusion of radiation dose and heat load

PR inputs tune PRAETOR for characterizing plutonium separation processes relative to other nuclear fuel cycle operations. PRAETOR uranium enrichment assessments are thereby impeded from reaching PR value near 1, since radiation dose and heat load are far less relevant PR attributes.

In a pure diversion scenario, a proliferator would remove the nuclear material in one theft, and in doing so to circumvent the material control and accountancy (MC&A) procedures. This risk makes pure diversion scenarios easier from a single weapon acquisition standpoint, but enhances the overall proliferation risk for a state that might only acquire enough material for a single weapon. With enough material verified for only a single weapon, a state proliferator might find itself more of a target for international intervention than possessing a valuable deterrent.

Using MAUA allows for balancing the technical complexity associated with uranium enrichment versus the increased material handling and processing difficulty for plutonium separation. By creating tier utility values between 0 and 1, MAUA ensures that reaching either extreme is very difficult. All the utility values must be either high or low to obtain a tier MAUA value of 0 or 1. With MAUA situations assessing trade-offs between different nuclear material acquisition routes, some of the input attribute utility values are oriented towards identifying a particular proliferation pathway. By extension, some of the input attribute utility values for a particular pathway are not geared towards detecting that type of proliferation. Therefore, although the maximum MAUA Overall PR is 1, the highest Overall PR for a realistic assessment obtained using PRAETOR is approximately 0.80. The lowest practical Overall PR is obtained using PRAETOR is about 0.1 for a proliferator diverting unsafeguarded plutonium for a plutonium implosion device.

Input Attribute Value Mapping to Utility Value

All of the sixty-three input attribute values supplied by the user to the PRAETOR code through the 'Uinput.i' input file are mapped to utility values ranging between 0 and 1 using the respective utility functions. The utility functions employed are briefly described here. The attribute value supplied by the user is designated as 'h' and the utility value as 'u' in the following equations. Refer to Appendix A for the range and unit of 'h' values.

Explanations for almost all of the utility functions were obtained can be found in References 13 and 14. The initial utility functions for the MAUA input attributes were determined during multiple consultations between nuclear nonproliferation experts at University of Texas-Austin, BWXT-Pantex, ORNL, SNL, and AREVA. The nuclear nonproliferation experts comprise a broad cross-section of knowledge from academia, the U.S. national laboratories, and industry. The diverse background of nuclear nonproliferation subject matter experts (SMEs) ensured several critical proliferation perspectives, and were addressed by the utility functions. Donald Giannangeli developed the majority of input attribute utility functions based on these discussion with the nonproliferation SMEs from the preceding organizations.[13] Richard Metcalf expanded on a few nuclear PR sections with additional input attributes; and, then Dr. Metcalf surveyed more American and international nuclear nonproliferation SMEs from academia, government, national laboratories, and industry to weight the input attributes used in PRAETOR.[14] For input attributes 1, 5, and 8 more in-depth explanations of the utility functions are provided as examples.

Stage I (Diversion), Subgroup 1: Material Handling Difficulty During Diversion

1. Mass per SQ of the nuclear material

$$u = e^{-[25(\frac{8}{h})]}$$

A number of factors make nuclear materials difficult to handle, even for the nuclear facility owner[13,14]. The mass per SQ of nuclear material, measured in units of kilograms per SQ, is one potential proliferation obstacle. This input considers the mass of the entire diverted object or quantity of solution which contains the fissile material of interest. Items or solutions that have a higher concentration of fissile material (and thus, a lower mass/SQ) will be more attractive to a proliferator since a lower total mass would need to be diverted and handled to acquire a useable significant quantity. The input uses the number of kilograms of material diverted to acquire one SQ of fissile material. SQs are defined by the IAEA to be 8 kg for Pu, 25 kg of ^{235}U for Highly-Enriched Uranium (HEU), 75 kg ^{235}U for Low-Enriched Uranium (LEU, uranium with < 20 percent ^{235}U), 10 MT for natural uranium (NatU, uranium with 0.72 percent ^{235}U) and 20 MT for thorium and depleted uranium (DepU, uranium with < 0.72 percent ^{235}U).

The use of SQs here allows us to normalize the input for all materials. A negative exponential utility function form was used with the SQ for HEU, 25 kg, and for Pu, 8 kg, in the exponential numerator and the input mass value in the denominator.

As the value of this input increases, the proliferator will need to take more time and/or use more equipment to move the amount of material needed for a nuclear weapon, thus increasing the material handling difficulty.

2. Volume per SQ of the nuclear material

$$u = e^{-[2000(\frac{0.000404}{h^{0.33}})]}$$

3. Number of items per SQ

$$u = 1 - e^{-[0.1h^{0.44}]}$$

4. Material form

$$u = 0.1; \text{if solid}$$
$$u = 0.5; \text{if powder}$$
$$u = 0.7; \text{if liquid}$$
$$u = 1.0; \text{if gas}$$

5. Radiation level in terms of dose

$$u = 0.0; h \leq 0.002$$
$$u = 1.30208h - 0.010416;\ 0.002 < h \leq 0.05$$
$$u = 0.089285h + 0.232142;\ 0.05 < h \leq 0.75$$
$$u = 0.0238095h + 0.4285714;\ 0.75 < h \leq 6.0$$
$$u = 1.0;\ h > 6.0$$

The utility function for radiation level in terms of dose for the unshielded material is based on measurements in Sieverts per hour per SQ.[13,14] The SQ basis is used to normalize the input over all fissile materials. This input considers the acute biological effects of whole-body radiation dose to the proliferator. At the lower range the input combines a small effect on PR for lower dose rates (above a threshold of 2 mSv/hr/SQ) for the costs of specialized equipment. High dose rate materials would be hazardous to handle and may require the use of expensive and unique equipment. Extremely high dose rate materials would also provide a danger to the physical well-being of the proliferator; therefore a threshold of 6 Sv/hr/SQ was considered to produce acute effects incapacitating the proliferator in a short time frame. Thus, radiation has a direct effect on the difficulty of handling a diverted material, increasing the difficulty with rising dose rates.

6. Chemical reactivity

The information regarding the chemical reactivity of the diverted material with substances such as air, water, steels and plastics is used here. If the material reacts rapidly with air, then it must be kept in an inert atmosphere as it is removed from a system and if it reacts quickly with water, that atmosphere will need to be dry. These constraints create significant handling difficulties for proliferators. Finally, if the material has slow reactions (i.e., corrosion, etc.) with steels and plastics it will limit the amount of time available for transport in such containers, a smaller difficulty. This input can be subjectively quantified according to Table 2. The user answers for each row of Table 2 questions with a y (yes) or n (no). The utility value for *u* is then obtained by adding the results from each row together with the following exceptions: if the answer is yes for both rows 3 and 5, only row 3 is used and likewise for rows 4 and 6.

7. Temperature of source process

$$u = 0.0; h < 20$$
$$u = 0.2282ln(h) - 0.6836;\ 20 < h \leq 1600$$
$$u = 1.0; h > 1600$$

8. Heat load of material

$$u = 0.0; h \leq 0.331$$
$$u = 0.2172ln(h) + 0.2407;\ 0.331 < h \leq 32.9$$
$$u = 1.0; h > 32.9$$

The heat load of the diverted material itself, measured in thermal watts per cubic centimeter of material, is used for the input attribute utility function.[13,14] Rather than focusing on the temperature of the system, as the previous input does, this is a measure of the rate at which the material itself generates heat, such as from the decay of radioactive isotopes. If this heat load is high enough, it will need to be mitigated with some kind of heat removal technique which must be applied during diversion. Also, increasing heat load will create a need for increasingly complex or large heat removal equipment.

For a minimum value, we can use a standard 100-W household light bulb which, based on its volume, emits about 0.5 W/cc of heat. Since these light bulbs can be cooled simply by natural convection in air, its PR value is set to zero. The heating rates of reactor grade Pu (0.25 W/cc) and PWR SNF (0.33 W/cc) fall below the 0.5 W/cc minimum, so their PR values are also zero. Operating reactors require the greatest cooling effort in the nuclear industry, usually with forced convection in water. An operating pressurized heavy-water reactor (PHWR) such as a CANDU produces 33 W/cc, so we will set this as the maximum value above which PR is equal to unity. An operating PWR produces more heat (330 W/cc) so its PR value is also unity. An intermediate value could be that for SNF in wet storage, because it can be cooled with natural convection in water. This material produces 3.3 W/cc of heat. This value is halfway between SNF dry storage and an operating PHWR on a logarithmic scale, so its PR value will be set to 0.5. Another intermediate example would be an operating high temperature gas-cooled reactor (HTGR) at 8 W/cc which must be cooled by forced convection in air. We will set this PR value to 0.75.

Stage I (Diversion), Subgroup 2: Difficulty in evading detection, material accounting & control system

9. Uncertainty of accountancy measurements

$u = 0.0; h > 1$
$u = 1 - h; h \leq 1$

10. Expected Vs. Actual material unaccounted for (MUF)

$u = -0.0333h + 1; h \leq 3.0$
$u = -0.1h + 1.2;\ 3.0 < h \leq 9.0$
$u = -0.01818h + 0.4636; 9.0 < h \leq 20.0$
$u = 0.1;\ h > 20$

11. Frequency of measurement

$u = 1.0$; if continuous
$u = 0.95$; if hourly
$u = 0.85$; if daily
$u = 0.75$; if weekly
$u = 0.5$; if monthly
$u = 0.25$; if quarterly
$u = 0.1$; if annually
$u = 0.0$; if never

12. Amount of material available

$u = 1 - (\frac{h}{50}); h < 20.0$
$u = 0.6 - 0.6(h - 20)/180;\ 20.0 < h \leq 200$
$u = 0.0;\ h > 200$

Stage I (Diversion), Subgroup 3: Difficulty of covertly making facility modification

13. Probability of detection

$$u = \left[\left(\frac{1 + 100}{1 + 100e^{-[0.1h]}}\right) - 1\right]/100$$

14. Is there space to modify?

$u = 0.0$; if yes
$u = 1.0$; if no

15. Number of people required for modifications

$$u = \left[\left(\frac{1 + 100}{1 + 100e^{-[0.1h]}}\right) - 1\right]/100$$

16. Whether remote handling tools required for modification?

$u = 1.0$; if yes
$u = 0.0$; if no

17. Whether specialized tools required for modification?

$u = 1.0$; if yes
$u = 0.0$; if no

18. Whether process halt is required for modification?

$u = 1.0$; if yes
$u = 0.0$; if no

19. Risk of modification

$u = 0.0; h < 1$
$u = 0.229921Ln(h + 1) + 0.3;\ h \geq 1$

20. Probability of penetrating containment

$$u = \left[\left(\frac{1 + 100}{1 + 100e^{-[0.1h]}}\right) - 1\right]/100$$

Stage I (Diversion), Subgroup 4: Difficulty of evading IAEA with covert facility modifications & process monitoring

21. Probability of getting caught by IAEA accounting

$$u = \left[\left(\frac{1 + 100}{1 + 100e^{-[0.1h]}}\right) - 1\right]/100$$

22. Probability of getting caught by process monitoring

$$u = \left[\left(\frac{1 + 100}{1 + 100e^{-[0.1h]}}\right) - 1\right]/100$$

Stage II (Transportation), Subgroup 1: Material handling difficulty during transportation

23. Mass per SQ of the nuclear material

$$u = e^{-[25(\frac{8}{h})]}$$

24. Volume per SQ of the nuclear material

$$u = e^{-[2000(\frac{0.000404}{h^{0.33}})]}$$

25. Material form

$u = 0.1$; if solid
$u = 0.5$; if powder
$u = 0.7$; if liquid
$u = 1.0$; if gas

26. Radiation level in terms of dose

$u = 0.0; h \leq 0.002$
$u = 1.30208h - 0.010416;\ 0.002 < h \leq 0.05$
$u = 0.089285h + 0.232142;\ 0.05 < h \leq 0.75$
$u = 0.0238095h + 0.4285714;\ 0.75 < h \leq 6.0$
$u = 1.0;\ h > 6.0$

27. Heat Load

$u = 0.0; h \leq 0.331$
$u = 0.2172Ln(h) + 0.2407;\ 0.331 < h \leq 32.9$
$u = 1.0; h > 32.9$

28. Chemical reactivity

Chemical reactivity of the diverted nuclear material can also create constraints for transporting the material to places where it can be transformed into weapons/explosive device usable material. Hence, chemical reactivity attribute is selected for the transportation stage also and the utility function used is the same as described above for input number 6.

29. Immediate chemical toxicity

Greater measures taken to protect humans transporting the chemically toxic diverted nuclear material will result in greater material handling difficulty. The Immediately Dangerous to Life and Health (IDLH) concentration of a material established by the U.S. Centers for Disease Control (CDC) deals with a substance's ability to rapidly incapacitate an individual.[33] The lower the IDLH concentration is for a material; the more difficult it will be to handle safely. The smallest concentration on this list (indicating the most toxic compound and a PR utility value of 1.0) is 1 ppm and the largest concentration (indicating the least toxic compound and a PR utility value of 0.0) is 10,000 ppm. The utility function is then a straight line on a logarithmic scale between these two extremes.

$u = 0.0; h > 10000$
$u = 1.0; h < 1$
$u = -0.1086ln(h) + 1;\ 1 \leq h < 10000$

30. Time averaged chemical toxicity

The other way to measure toxicity is a time-weighted average (TWA) concentration which, if exceeded for a length of time, would pose health risks. TWA toxicity, then, deals with long-term health effects and would be of little concern if the transportation stage does not take much time. However, if the transport takes very long, then measures will be needed to mitigate the risk. The difficulty will increase as the TWA concentration decreases. The U.S. Occupational Safety and Health Administration (OSHA) maintain a list of time-weighted average air concentrations of compounds that a worker should not be exposed to over the course of an eight-hour work shift.[34] Violation of this average limit could result in long-term health effects. Other countries may have different standards than the United States, but using the OSHA values in the code of federal regulation (CFR) provides a good ranking of chemicals from most to least toxic due to chronic exposure.[34] The smallest average concentration on this list (indicating the most toxic compound and a PR utility value of 1.0) is 0.001 ppm over eight hours and the largest average concentration (indicating the least toxic compound and a PR utility value of 0.0) is 1,000 ppm over eight hours. The utility function is then a straight line on a log scale between these two extremes. Both for this input and the previous IDLH toxicity input, if a compound is not found on the lists, it will be assumed that it is not toxic and assign a PR value of zero.

$u = 0.0; h > 1000$
$u = 1.0; h < 0.001$
$u = -0.0724ln(h) + 0.5;\ 0.001 \leq h < 1000$

Stage II (Transportation), Subgroup 2: Difficulty of evading detection during transport

31. Mass of material and transportation container

$u = 0.0; h \leq 100.1$
$u = 1.0; h > 90000$
$u = 0.147ln(h) - 0.677;\ 100.1 < h \leq 90000$

32. Volume of material and transportation container

$u = 0.0; h < 1$
$u = 1.0; h > 700$
$u = 0.1526ln(h);\ 1 \leq h \leq 700$

33. Heat load of material

$u = 0.0; h \leq 0.331$
$u = 0.2172ln(h) + 0.2407;\ 0.331 < h \leq 32.9$
$u = 1.0; h > 32.9$

34. Shield thickness required to reduce radiation field to 10mR/hr

$u = 0.5h$
$u = 1.0; h > 2$

35. Host country size

$$u = 0.0; h > 17000000$$
$$u = -0.1133 ln(h) + 1.8862;\ 2500 \leq h \leq 17000000$$
$$u = 1.0; h < 2500$$

36. Number of declared nuclear facilities

$$u = 0.0; h > 100$$
$$u = -0.01(h) + 1.01;\ 1 \leq h \leq 100$$

37. IAEA imagery analysis rate

$$u = 0.6; h > 0.30$$
$$u = 2h; 0 < h \leq 0.30$$

Stage III (Transformation), Subgroup 1: Facilities and equipment needed to process diverted materials

38. Number of process steps to metallic form

Each process step requires its own set of skills and specific knowledge. The more steps there are the more types of expertise that are needed. This input will be a measure of the number of different chemical procedures that must be performed on a material to transform it from its diverted form into a weapons-usable metal. The steps involved are listed in Table 3 and the utility function is chosen to represent a direct relationship between the number of process steps to metallic form and the difficulty in completing the material transformation.

$$u = \frac{h}{11.};\ 1 \leq h \leq 11$$

39. Number of export control equipment/materials required

This attribute is the number of different types of export controlled equipment and materials that the proliferators need to complete the transformation process. IAEA INFCIRC/254 parts 1 and 2 give a combined list of 178 different types of equipment, tools, materials, software, and complete facilities that could make a significant contribution to a nuclear explosive program, undeclared fuel cycle facility or nuclear terrorism. Export of these items is restricted. The more of these things that proliferators need to build a weapon out of the diverted material, the greater will be his difficulty in achieving his goal. Following is the utility function for this attribute and is an additive relationship between PR and the number of items from the list that are needed.

$$u = 1.0;\ h > 178$$
$$u = 0.0056h;\ 0 \leq h \leq 178$$

Stage III (Transformation), Subgroup 2: Workforce required for transformation

40. Minimum electrical requirement

$$u = 1.0;\ h > 3360$$
$$u = 0.1219 Ln(h);\ 1 \leq h \leq 3360$$

41. Number of unskilled workers required

$$u = 1.0;\ h > 3000$$
$$u = \left[\left(\frac{50}{1 + 50e^{-[0.0212h]}}\right) - 1\right]/50;\ h \leq 300$$

42. Number of skilled workers required

$$u = 1.0;\ h > 500$$
$$u = \left[\left(\frac{58}{1 + 58e^{-[0.055h]}}\right) - 1\right]/58;\ h \leq 500$$

43. Number of advanced degree workers required

$$u = 1.0;\ h > 200$$
$$u = \left[\left(\frac{56}{1 + 56e^{-[0.128h]}}\right) - 1\right]/56;\ h \leq 200$$

44. Number of technical experts required

$$u = 1.0;\ h > 85$$
$$u = \left[\left(\frac{55}{1 + 55e^{-[0.25h]}}\right) - 1\right]/55;\ h \leq 85$$

Stage III (Transformation), Subgroup 3: Difficulty of evading detection of transformation activities

45. IAEA Additional Protocol in force?

The presence of the additional protocol in force allows for additional detection options for the IAEA. Inputs 46, 47, and 48 may be available provided the IAEA has the access capabilities associated with a country signing the Additional Protocol.

$$u = 0;\ \text{if “no” to additional protocol}$$
$$u = 1;\ \text{if “yes” to additional protocol}$$

46. Long-range environmental sampling rate

Long range environmental sampling encompasses a large area detection capability, up to several kilometers in radius, deployed in the immediate vicinity of a known or suspected nuclear facility.[35-37] Long range environmental sampling increases a proliferator’s detection probability for co-locating covert nuclear proliferation activities near declared nuclear facilities.

$$u = 1.0;\ h > 8.05$$
$$u = 0.0203h^2 - 0.0467h + 0.0578;\ 1 < h \leq 8.05$$
$$u = 0.0187h;\ 0 \leq h \leq 1$$

47. Sensitivity of IAEA equipment

$u = 0.0;\ h \geq 20$

$u = e^{-[(\frac{h}{10})]};\ h < 20$

48. Isotopic signatures

$u = 0.2h;\ 0 \leq h \leq 5$

49. Facility size

$u = 0.0;\ h < 101$

$u = 0.1563ln(h) - 0.7199;\ 101 \leq h \leq 60000$

$u = 1.0;\ h > 60000$

50. Heat load of transformation process

$u = 0.0;\ h < 0.0001$

$u = 0.0587ln(h) + 0.5407;\ 0.0001 \leq h \leq 2500$

$u = 1.0;\ h > 2500$

51. Sonic load

$u = 0.0071h + 0.5407;\ 0.0 \leq h \leq 140$

$u = 1.0;\ h > 140$

52. Radiation load

$u = 0.0;\ h < 0.01001$

$u = 0.08686ln(h) + 0.4;\ 0.01001 \leq h \leq 1000$

$u = 1.0;\ h > 1000$

53. Volume of non-naturally occurring gases emitted

$u = 0.0;\ h < 1.02E - 06$

$u = 0.0337Ln(h) + 0.465; 1.02E - 06 \leq h \leq 7.8E + 06$

$u = 1.0;\ h > 7.8E + 06$

54. Volume of undiluted radioactive liquid emissions

$u = 0.0;\ h < 1.02E - 06$

$u = 0.0376Ln(h) + 0.5189; 1.02E - 06 \leq h \leq 3.65E + 05$

$u = 1.0;\ h > 3.65E + 05$

Stage IV (Weaponization), Subgroup 1: Difficulty associated with design

55. Spontaneous fission neutron emission rate

$u = 1 - e^{-3.5(h/2700)^{1.8}}$

56. Radiation exposure at one meter

$u = 0.0;\ h < 0.01001$

$u = 0.08686Ln(h) + 0.4;\ 0.01001 \leq h \leq 1000$

$u = 1.0;\ h > 1000$

57. Heating rate of weapons material

$u = 1.0;\ h > 1000$

58. Whether ballistic assembly methods can be used?

$u = 0$; if "yes"

$u = 1$; if "no"

59. Number of phases in nuclear material phase diagram

$u = 0.1667h - 0.1667;\ 1 \leq h \leq 7$

$u = 1.0;\ h > 7$

Stage IV (Weaponization), Subgroup 2: Handling difficulty and skills for design

60. Radiation level in terms of dose

$u = 0.0; h \leq 0.002$

$u = 1.30208h - 0.010416;\ 0.002 < h \leq 0.05$

$u = 0.089285h + 0.232142;\ 0.05 < h \leq 0.75$

$u = 0.0238095h + 0.4285714;\ 0.75 < h \leq 6.0$

$u = 1.0;\ h > 6.0$

61. Chemical reactivity

Chemical reactivity of the transformed nuclear material can also create constraints while fabricating a weapon or explosive device. Hence, the chemical reactivity attribute is also selected for the weaponization stage and the utility function used is the same as described above for input number 6.

62. Radiotoxicity

This input requires a knowledge or prediction of the isotopic composition of the weapons-usable material produced in the transformation stage. Carter (1993) classifies radionuclides into four levels of radio-toxicity: very high, high, moderate, and low. Carter's table of nuclide classifications is reproduced in Table 4.[33] Weighting factors of 1, 0.75, 0.5 and 0.25 are assigned to each of these Group 1, Group 2, Group 3, and Group 4 classifications respectively.

$u = h$

63. Knowledge and skills needed to design and fabricate

The technical and human capital difficulties associated with creating different nuclear weapon designs as a fraction between 0 and 1. The fractional difficulty associated with fabrication of highly enriched uranium, with greater than 93 percent ^{235}U, nuclear weapon delivered via truck (u ~ 0) is much lower than for a reactor grade plutonium nuclear weapon delivered via a small missile warhead (u ~ 1).

$u = h$

PRAETOR Code Input

The PRAETOR code needs two user input files. The first file is named uinput.i and contains numeric values or string text inputs as appropriate for all of the sixty-three attributes (refer to Table 1 for the list of attributes). The attribute values entered describe the characteristics with respect to diverting, transporting, transforming and weaponization from one SQ worth of SNM contained in material diverted. Appendix A contains the complete list of attributes, information on their range and the units in which they need to be entered in the input file. The second input file supplied by the user contains the weight values required for the MAUA. If the user opts to use uniform weighting scheme, the file named norm.i is read by the code. Instead if the user opts for weights based on an expert survey, the file named expsur.i is used. Expert weights for each of the sixty-three attributes are listed in Appendix A. Expert weights for the sub-groups and stages are included in Appendix B. Either of these input files should contain the weight values for the four major groups, eleven subgroups and all of the sixty-three attributes. An extensive user's manual for PRAETOR code is available.[32]

PRAETOR Code Package and Output

The PRAETOR code package comes with a file named PRAETOR.exe, which is the only executable file needed to execute the code under the Microsoft Windows platform. The source code, PRAETOR.f90 can be compiled to produce the executable on UNIX/Linux platforms also. The Fortran compilers GFortran and Intel Fortran 10 were able to compile the code on both Windows and Linux platforms. Details on how to execute the code can be found in user's manual.[32] A flow chart showing the actions performed by the PRAETOR code is shown in Figure 2.

The output file of the PRAETOR code contains:

1. Utility values generated for each user supplied attribute value
2. PR values at each of the three tiers of MAUA in order to aid the user to find out which stage or sub-group contributed most towards the final or overall PR value obtained at the third tier.

The output file information would facilitate safeguards analysis and development. The overall PR value in the output file should be used only for comparison to a different scenario. That is the PR value by itself for one scenario doesn't have much meaning unless it is used to compare with the PR value for another SNM diversion/theft scenario. Therefore, the PRAETOR code results are most useful to compare the PR values between two or more SNM diversion/theft scenarios and to identify the relative strengths against proliferation of SNM within a single system or between systems under consideration. The results should also aid in developing a risk informed safeguards system.

Examples of PR Analyses Using PRAETOR Code

A comparison of two different PWR spent fuel assembly diversion scenarios is discussed here to demonstrate the input preparation and subsequent PR assessment using PRAETOR. The two diversion scenarios are: (1) PWR spent fuel assemblies (zero days cooled) from a storage facility and (2) PWR spent fuel assemblies (thirty years cooled) from a storage facility. The assumption is that an amount equivalent to 1 SQ of SNM could be derived from the diverted material in each diversion scenario. The input values and importance expert survey weights for each of the sixty-three attributes are included in the last three columns of the Appendix A table.

PRAETOR Input for Example Diversion Cases

The last two columns for Table in Appendix A include the input attribute values for the PWR spent fuel assemblies that has been (1) immediately removed from the reactor and (2) cooled for thirty years. The two examples outlined show how PRAETOR handles perturbations between two similar cases. The impact of cooling time allowances for lower activity in the PWR spent fuel assembly due to radioactive decay is reflected in Tables VA and VB and these tables depicts PRAETOR output results obtained for both additive and multiplicative MAUA.

Scenario 1 – Diversion of Non-Cooled PWR Spent Fuel Assemblies

Summary of the PR results (utility values) obtained from PRAETOR output for scenario-1 (diversion of PWR spent fuel assemblies which has seen no period of cooling) for all the three tiers of analysis is shown in Table 5A. The additive and multiplicative MAUA forms are included in Table 5A using expert elicitation survey weights. The following assessment is for the multiplicative MAUA PRAETOR computation. The overall PR value (0.479) is relatively higher value. To understand the reasons for this refer to the utility values obtained at the second tier for the four major stages. These values are 0.624

(diversion), 0.531 (transportation), 0.176 (transformation), and 0.478 (weapon fabrication). The contributing factor for the high overall PR value is from the stages of diversion, transportation, and weaponization, maximum being from diversion stage. The highest contribution at the diversion stage is coming from the sub-group attributes belonging to Difficulty of evading detection by the accounting and material control system.

Scenario 2 – Diversion of Thirty Years-Cooled PWR Spent Fuel Assemblies

Summary of the PR results (utility values) obtained from PRAETOR output for scenario-2 (diversion of PWR spent fuel assemblies that has seen thirty years of cooling) for all the three tiers of analysis is shown in Table 5B. The following assessment is for the multiplicative MAUA PRAETOR computation. The overall PR value (0.459) is relatively higher value marginally lower than the similar case of scenario 1. To understand the reasons for this refer to the utility values obtained at the second tier for the four major stages. These values are 0.617 (diversion), 0.447 (transportation), 0.169 (transformation), and 0.478 (weapon fabrication). The reason for a marginally lower overall PR value is the reduction in radiation dose rate from the cooled PWR assemblies and relatively lower shielding requirement during transport, which is reflected in the Material handling difficulty and Difficulty of evading detection sub-group values.

Conclusion

A computer code named, PRAETOR (Proliferation Resistance Analysis and Evaluation Tool for Observed Risk) has been developed to aid in comparing the proliferation resistance (PR) of nuclear installations. The well-established decision analysis methodology called Multi-Attribute Utility Analysis (MAUA) is the backbone for the code and is coded using Fortran 90 programming language. The PRAETOR code employs a metric, which considers both intrinsic and extrinsic measures at a nuclear installation to prevent SNM proliferation. Currently, the nonproliferation metric computed by PRAETOR code is based on sixty-three inputs. These attributes capture both intrinsic and extrinsic proliferation resistance characteristics of nuclear installation being analyzed for quantifying PR. The PRAETOR code derives a single metric for nonproliferation performance comparison by appropriately folding the sixty-three inputs and their respective weights (relative importance) through MAUA methodology. The code was tested for various nuclear material diversion scenarios for a set of nuclear fuel cycle installations.

Future Work

The attributes used in the current version of the PRAETOR code are selected so as to perform technical assessments of proliferation resistance of the nuclear energy systems. Risk quantification is an aspect which could be added to the analysis. Conducting in depth sensitivity studies would indicate situations where the system PR has the greatest variability and would most benefit from additional nuclear safeguards. Publication of a range of proliferation scenario assessments using PRAETOR would demonstrate a wide set of applicable nuclear fuel cycle situations for PR analysis.

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Keywords: proliferation resistance metric, multi-attribute utility analysis, special nuclear material diversion, significant quantity, praetor

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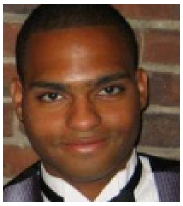

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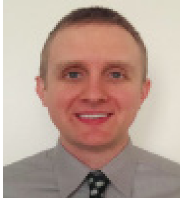

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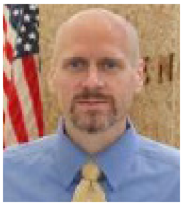

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Figure 1. Sequence of three-tier MAUA in PRAETOR

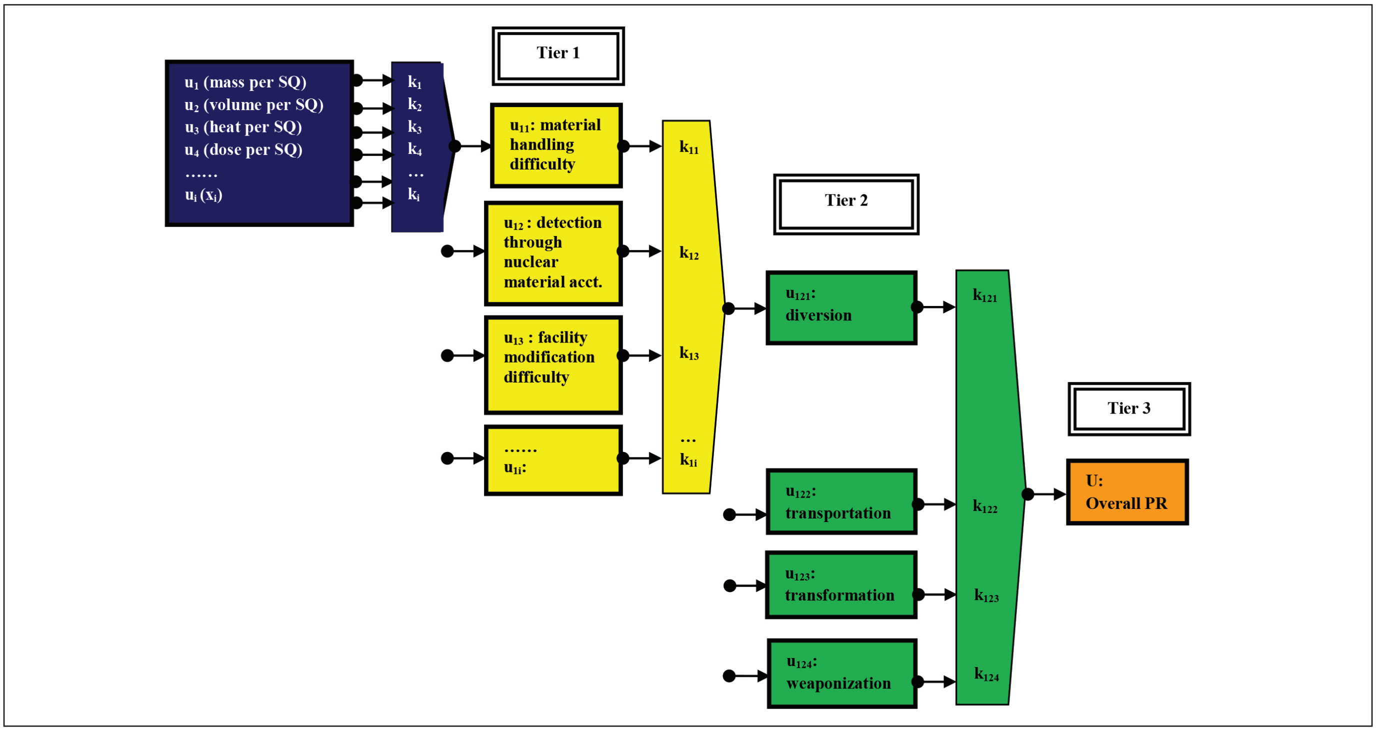
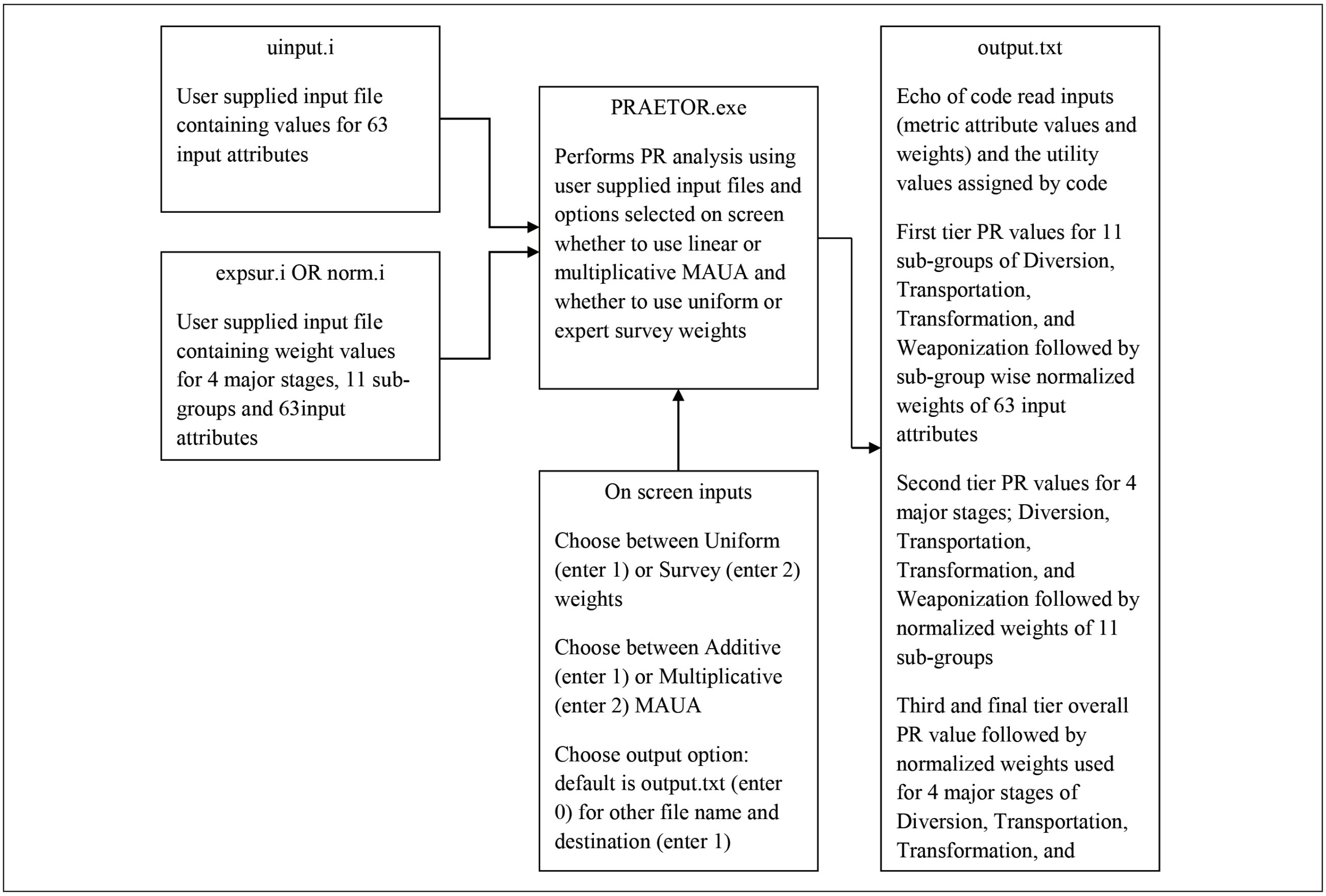


Figure 2. Flow chart of PRAETOR code



uinput.i

User supplied input file containing values for 63 input attributes

expsur.i OR norm.i

User supplied input file containing weight values for 4 major stages, 11 sub-groups and 63input attributes

PRAETOR.exe

Performs PR analysis using user supplied input files and options selected on screen whether to use linear or multiplicative MAUA and whether to use uniform or expert survey weights

On screen inputs

Choose between Uniform (enter 1) or Survey (enter 2) weights

Choose between Additive (enter 1) or Multiplicative (enter 2) MAUA

Choose output option: default is output.txt (enter 0) for other file name and destination (enter 1)

output.txt

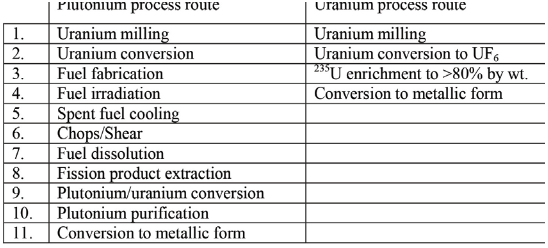
Echo of code read inputs (metric attribute values and weights) and the utility values assigned by code

First tier PR values for 11 sub-groups of Diversion, Transportation, Transformation, and Weaponization followed by sub-group wise normalized weights of 63 input attributes

Second tier PR values for 4 major stages; Diversion, Transportation, Transformation, and Weaponization followed by normalized weights of 11 sub-groups

Third and final tier overall PR value followed by normalized weights used for 4 major stages of Diversion, Transportation, Transformation, and

Table 2. Utility values for chemical reactivity



	Plutonium process route	Uranium process route
1.	Uranium milling	Uranium milling
2.	Uranium conversion	Uranium conversion to UF_6
3.	Fuel fabrication	^{235}U enrichment to >80% by wt.
4.	Fuel irradiation	Conversion to metallic form
5.	Spent fuel cooling	
6.	Chops/Shear	
7.	Fuel dissolution	
8.	Fission product extraction	
9.	Plutonium/uranium conversion	
10.	Plutonium purification	
11.	Conversion to metallic form	

Table 3. Process steps to metallic form (related to facilities)

	Plutonium process route	Uranium process route
1.	Uranium milling	Uranium milling
2.	Uranium conversion	Uranium conversion to UF_6
3.	Fuel fabrication	^{235}U enrichment to >80% by wt.
4.	Fuel irradiation	Conversion to metallic form
5.	Spent fuel cooling	
6.	Chops/Shear	
7.	Fuel dissolution	
8.	Fission product extraction	
9.	Plutonium/uranium conversion	
10.	Plutonium purification	
11.	Conversion to metallic form	

Table 4. Isotopes classified by radio-toxicity levels

Group 1 Very High Hazard	Group 2 High Hazard			Group 3 Moderate Hazard			Group 4 Low Hazard
^{227}Ac	^{105}Ag	^{254}Fm	^{242}Pu	^{238}Am	^{132}I^{m}	^{80}Sr	^{237}Am
^{237}Am	^{110}Ag^{m}	^{255}Fm	^{226}Ra	^{239}Am	^{134}I	^{83}Sr	^{36}Cl
^{249}Bk	^{111}Ag	^{153}Gd	^{86}Rb	^{240}Am	^{135}I	^{91}Sr	^{135}Cs
^{144}Ce	^{243}Am	^{181}Hf	^{103}Ru	^{244}Am^{m}	^{113}In^{m}	^{92}Sr	^{135}Cs^{m}
^{246}Cf	^{244}Am	^{203}Hg	^{122}Sb	^{245}Am	^{115}In^{m}	^{96}Tc	^{129}I
^{248}Cf	^{73}As	^{166}Ho	^{124}Sb	^{246}Am	^{42}K	^{99}Tc^{m}	^{53}Mn
^{249}Cf	^{74}As	^{124}I	^{125}Sb	^{246}Am^{m}	^{43}K	^{116}Te	^{88}Nb
^{250}Cf	^{76}As	^{125}I	^{46}Sc	^{77}As	^{177}Lu	^{121}Te	^{59}Ni
^{251}Cf	^{211}At	^{126}I	^{48}Sc	^{199}Au	^{51}Mn	^{127}Te	^{193}Pt
^{252}Cf	^{198}Au	^{130}I	^{75}Se	^{7}Be	^{56}Mn	^{131}Te	^{244}Pu
^{253}Cf	^{140}Ba	^{131}I	^{113}Sn	^{82}Br	^{90}Mo	^{133}Te^{m}	^{97}Tc
^{254}Cf	^{206}Bi	^{133}I	^{125}Sn	^{14}C	^{93}Mo^{m}	^{231}Th	^{99}Tc
^{240}Cm	^{207}Bi	^{114}In^{m}	^{85}Sr	^{135}Ce	^{101}Mo	^{200}Tl	^{nat}Th
^{242}Cm	^{210}Bi	^{190}Ir	^{183}Ta	^{137}Ce^{m}	^{24}Na	^{202}Tl	^{ore}Th
^{243}Cm	^{212}Bi	^{192}Ir	^{160}Tb	^{38}Cl	^{89}Nb	^{231}U	^{232}Th
^{244}Cm	^{250}Bk	^{194}Ir	^{121}Te^{m}	^{247}Cm	^{89}Nb^{m}	^{236}U	^{nat}U
^{245}Cm	^{45}Ca	^{140}La	^{123}Te	^{55}Co	^{90}Nb	^{240}U	^{ore}U
^{246}Cm	^{47}Ca	^{52}Mn	^{123}Te^{m}	^{61}Co	^{94}Nb	^{187}W	^{235}U
^{253}Es	^{109}Cd	^{54}Mn	^{125}Te^{m}	^{51}Cr	^{95}Nb^{m}	^{92}Y	^{238}U
^{254}Es	^{115}Cd^{m}	^{93}Mo	^{127}Te^{m}	^{132}Cs	^{149}Nd	^{93}Y	^{93}Zr
^{254}Es^{m}	^{115}Cd	^{99}Mo	^{129}Te^{m}	^{138}Cs	^{237}Np	^{86}Zr	
^{257}Fm	^{134}Ce	^{22}Na	^{131}Te^{m}	^{64}Cu	^{191}Os^{m}	^{89}Zr	
^{230}Pa	^{139}Ce	^{93}Nb^{m}	^{132}Te	^{165}Dy	^{193}Os		
^{210}Pb	^{141}Ce	^{95}Nb	^{226}Th	^{169}Er	^{33}P		
^{210}Po	^{143}Ce	^{96}Nb	^{234}Th	^{171}Er	^{203}Pb		
^{236}Pu	^{244}Cf	^{147}Nd	^{170}Tm	^{152}Eu^{m}	^{103}Pd		
^{238}Pu	^{238}Cm	^{239}Np	^{171}Tm	^{18}F	^{109}Pd		
^{241}Pu	^{241}Cm	^{185}Os	^{233}U	^{52}Fe	^{203}Po		
^{223}Ra	^{248}Cm	^{191}OS	^{234}U	^{55}Fe	^{191}Pt		
^{224}Ra	^{56}Co	^{32}P	^{237}U	^{72}Ga	^{193}Pt^{m}		
^{225}Ra	^{57}Co	^{231}Pa	^{48}V	^{159}Gd	^{197}Pt		
^{226}Ra+d	^{58}Co	^{233}Pa	^{90}Y	^{3}H	^{237}Pu		
^{228}Ra	^{60}Co	^{212}Pb	^{91}Y	^{197}Hg	^{245}Pu		
^{106}Ru	^{134}Cs	^{147}Pm	^{65}Zn	^{197}Hg^{m}	^{227}Ra		
^{90}Sr	^{136}Cs	^{149}Pm	^{88}Zr	^{120}I	^{105}Rh		
^{90}Y+^{90}Sr	^{137}Cs	^{142}Pr	^{95}Zr	^{120}I^{m}	^{97}Ru		
^{227}Th	^{166}Dy	^{143}Pr	^{97}Zr	^{121}I	^{35}S		
228Th	^{152}Eu	^{234}Pu		^{123}I	^{47}Sc		
^{229}Th	^{154}Eu	^{239}Pu		^{128}I	^{151}Sm		
^{230}U	^{155}Eu	^{240}Pu		^{132}I	^{153}Sm		
^{232}U	^{59}Fe						

Table 5A. PRAETOR Code output summary for PWR spent fuel assembly (non-cooled) diversion

11 Sub-groups of 4 Major Stages at Tier 1 MAUA	PRAETOR Utility Values Using Expert Elicitation Weighting Additive / Multiplicative)		
	Tier 1	Tier 2	Tier 3
Material handling difficulty	0.468 / 0.496		
Difficulty of evading detection by the accounting and material control system	0.859 / 0.879		
Difficulty of covertly making facility modifications	0.437 / 0.465		
Difficulty of evading IAEA with covert facility modifications and process monitoring	0.498 / 0.547		
		0.568 / 0.624 (Diversion)	
Material handling difficulty	0.500 / 0.529		
Difficulty of evading detection	0.456 / 0.482		
		0.479 / 0.531 (Transportation)	
Facilities & equipment need for processing	0.238 / 0.260		
Workforce requirement	0.022 / 0.024		
Difficulty of evading detection	0.198 / 0.215		
		0.148 / 0.176 (Transformation)	
Difficulty associated with design	0.441 / 0.473		
Handling difficulties & knowledge skills for design	0.400 / 0.427		
		0.423 / 0.478 (Weaponization)	
			0.406 / 0.479

Table 5B. PRAETOR Code output summary for PWR spent fuel assembly (30 years cooled) diversion

11 Sub-groups of 4 Major Stages at Tier 1 MAUA	PRAETOR Utility Values Using Expert Elicitation Weighting (Additive / Multiplicative)		
	Tier 1	Tier 2	Tier 3
Material handling difficulty	0.438 / 0.466		
Difficulty of evading detection by the accounting and material control system	0.859 / 0.879		
Difficulty of covertly making facility modifications	0.437 / 0.465		
Difficulty of evading IAEA with covert facility modifications and process monitoring	0.498 / 0.547		
		0.560 / 0.617 (Diversion)	
Material handling difficulty	0.453 / 0.482		
Difficulty of evading detection	0.337 / 0.360		
		0.396 / 0. 447 (Transportation)	
Facilities & equipment need for processing	0.238 / 0.260		
Workforce requirement	0.022 / 0.024		
Difficulty of evading detection	0.179 / 0.194		
		0.143 / 0.169 (Transformation)	
Difficulty associated with design	0.441 / 0.473		
Handling difficulties & knowledge skills for design	0.400 / 0.427		
		0.423 / 0.478 (Weaponization)	
			0.387 / 0.459

Appendix A.

PRAETOR Code output summary for PWR spent fuel assembly (non-cooled) diversion

Serial No.	Input Descriptions	Units	Range		Scenario		Expert Survey Weights
			Low ($u_i \sim 0$)	High ($u_i \sim 1$)	Spent PWR Fuel 1	2	
1	Mass/SQ of the Nuclear material	kg/SQ	8	10000	1315.8	1315.8	1.78E-01
2	Volume/SQ of the Nuclear material	m^3/SQ	0.001	1000000	0.372	0.372	1.70E-01
3	Number of Items/SQ	Items/SQ	1	6000	2	2	1.62E-01
4	Material Form	Solid, Liquid, Powder, Gas	Solid	Gas	Solid	Solid	8.04E-02
5	Radiation level in terms of dose	Sv/hr/SQ	0.002	6	9.70E+04	1.67E+01	1.86E-01
6	Chemical Reactivity	Answer yes with 'y'/no with 'n' to the following: 1. Air (fast), 2. Water (fast), 3. Steel (fast), 4. Plastic (fast), 5 Steel (slow), 6. Plastic (slow)	nnnnnn	yyyyyy	nnnnyy	nnnnyy	7.60E-02
7	Temperature of Source Process	Degree Celsius	20	1600	20	20	8.86E-02
8	Heat Load of Material	Watts/cm^3	0.33	33	3.28	0.0028	5.96E-02
9	Uncertainty of Accountancy Measurements	Units of SQ/year (measurement uncertainty per SQ x number SQ's processed through the facility in one year)	1	0	0	0	2.81E-01
10	Expected Vs. Actual MUF	Measured in SQ's	20	0	0	0	2.81E-01
11	Frequency of Measurement	Never, Annually, Quarterly, Monthly, Weekly, Daily, Hourly, Continuous	Never	Continuous	quarterly	quarterly	2.03E-01
12	Amount of Material Available	Number of SQ's	200	0	60	60	2.34E-01
13	Probability of Detection	Probability in percent	1.00E-03	100	100	100	1.00E+00

Appendix A. (cont.)

PRAETOR Code output summary for PWR spent fuel assembly (non-cooled) diversion

14	Is there Space to Modify	No(0)/yes(1)	1	0	0	0	1.73E-01
15	Number of people required for modifications	Count	1.00E-05	150	1.00E-05	1.00E-05	1.73E-01
16	Remote Handling Tools Required?	Yes(1)/no(0)	0	1	0	0	1.26E-01
17	Specialized Tools Required?	Yes(1)/no(0)	0	1	0	0	1.26E-01
18	Require Process Halt for Modification	Yes(1)/no(0)	0	1	0	0	1.35E-01
19	Risk of Modification	Number of lives lost	0	20	20	20	1.26E-01
20	Probability of Penetrating Containment	Probability in percent	1.00E-03	100	80	80	1.43E-01
21	Probability of Detection by IAEA Accounting	Probability in percent	1.00E-03	100	100	100	5.00E-01
22	Probability of Detection by Process Monitoring	Probability in percent	1.00E-03	100	1.00E-03	1.00E-03	5.00E-01
23	Mass/SQ of Nuclear Material	kg/SQ	8	10000	1315.8	1315.8	1.91E-01
24	Volume/SQ of Nuclear Material	m^3/SQ	0.001	1000000	0.372	0.372	1.82E-01
25	Material Form	Solid, Liquid, Powder, Gas	solid	Gas	solid	solid	1.24E-01
26	Radiation Level in Terms of Dose	Sv/hr/sq	0.002	6	9.70E+04	1.69E+02	2.07E-01
27	Heat Load of Material	Watts/cm^3	0.33	33	3.28	0.0028	9.45E-02
28	Chemical Reactivity	Answer 'yes'/'no' to the following: 1. Air (fast), 2. Water (fast), 3. Steel (fast), 4. Plastic (fast), 5 Steel (slow), 6. Plastic (slow)	nnnnnn	yyyyyy	nnnnyy	nnnnyy	5.35E-02
29	Immediate Chemical Toxicity	parts per million (least ppm most toxic)	10000	1	10001	10001	6.99E-02
30	Time Average Chemical toxicity	parts per million (least ppm most toxic)	1000	0.001	1001	1001	7.81E-02

31	Mass of Material and Transportation Container	Kg	100	90000	25000	10874.42	1.89E-01
32	Volume of Material and Transportation Container	m^3	1	700	16.04	1.52	1.51E-01
33	Heat Load of Material	Watts/cm^3	0.33	33	0.038	0.0028	1.04E-01
34	Shield Thickness to reduce to 10mR/hr	Meter	0	2	0.915	0.1	1.04E-01
35	Host Country Size	km^2	17000000	2500	3287590	3287590	1.60E-01
36	Number of Declared Nuclear Facilities	Count	100	1	50	50	1.51E-01
37	IAEA Imagery Analysis Rate	Count/month	0	0.3 (max u of 0.60)	1	1	1.42E-01
38	Number of Process Steps to Metallic Form	Count- table	0	11	7	7	3.40E-01
39	Number of Export Controlled Equipment/Materials	Count	0	178	10	10	3.77E-01
40	Minimum Electrical Requirement	MWe	1	3360	1	1	2.82E-01
41	Number of Unskilled Workers required	Person years	11	600	25	25	1.25E-01
42	Number of Skilled workers Required	Person years	3	200	10	10	2.73E-01
43	Number of Advanced degree workers	Person years	1	80	5	5	3.08E-01
44	Number of Technical Experts Required	Person years	1	30	5	5	2.94E-01
45	Additional Protocol in Force	Yes(1)/no(0)	0	1	0	0	1.44E-01
46	Long Range Environmental Sampling Rate	Count/month/facility	0	8.05	0	0	1.19E-01
47	Sensitivity of IAEA Equipment	% error rate of the IAEA diversion detection system measurements	20	0	20	20	1.56E-01
48	Isotopic Signatures	Count- table	0	5	0	0	1.50E-01
49	Facility Size	m^2	0	60000	600	600	1.36E-01
50	Heat Load of Transformation Process	MWth	0.0001	2500	0.0001	0.0001	6.15E-02
51	Sonic Load	dB	0	140	0	0	5.58E-02

Appendix A. (cont.)

PRAETOR Code output summary for PWR spent fuel assembly (non-cooled) diversion

52	Radiation Load	R/hr	0	1000	9.70E+06	1.67E+03	5.00E-02
53	Volume of Non-Naturally Occurring gases emitted	Ci/yr	1.00E-06	8.00E+06	1.47E+06	1.45E+03	6.73E-02
54	Undiluted Volume of Liquid Emissions	Ci/yr	1.00E-06	3.65E+05	6.43E+02	1.52E+02	6.15E-02
55	Spontaneous Fission Neutron Production Rate	n/s/g	0	2700	400.58	400.58	1.97E-01
56	Radiation Exposure at 1m	R/hr	0	1000	0.003647	0.003647	1.59E-01
57	Heating Rate of Weapons Material	W/kg	0	171	84	84	1.37E-01
58	Can use Ballistic Assembly Methods	Yes(1)/no(0)	1	0	1	1	1.99E-01
59	Number of Phases in Phase Diagram	Count	1	7	7	7	3.08E-01
60	Radiation Level in Terms of Dose	Sv/hr/SQ	0.002	6	3.647E-05	3.65E-05	3.37E-01
61	Chemical Reactivity	Answer ‘yes’/’no’ to the following: 1. Air (fast), 2. Water (fast), 3. Steel (fast), 4. Plastic (fast), 5 Steel (slow), 6. Plastic (slow)	nnnnnn	yyyyyy	nnnnyy	nnnnyy	3.59E-01
62	Radio-toxicity	Isotopic Composition	0	1	0.75	0.75	3.04E-01
63	Knowledge and Skills Needed to Design and Fabricate	Direct input from calculation (least skills input is zero leads to U=0, most skills input is 1 leads to U=1)	0	1	0.5	0.5	1.00E+00

Appendix B.

List of expert elicited survey weights for tier 2, stages, and tier 1, sub-groups

Category	Weights
Group 1: Diversion	0.333
Sub-Group 1: Material handling difficulty during diversion	0.175
Sub-Group 2: Difficulty in evading detection, material accounting & control system	0.173
Sub-Group 3: Difficulty of covertly making facility modification	0.157
Sub-Group 4: Difficulty of evading IAEA with covert facility modifications & process monitoring	0.173
Group 2: Transportation	0.186
Sub-Group 5: Material handling difficulty during transportation	0.51
Sub-Group 6: Difficulty of evading detection during transport	0.49
Group 3: Transformation	0.277
Sub-Group 7: Facilities and equipment needed to process diverted materials	0.338
Sub-Group 8: Workforce required for transformation	0.357
Sub-Group 9: Difficulty of evading detection of transformation activities	0.301
Group 4: Weaponization	0.223
Sub-Group 10: Difficulty associated with design	0.353
Sub-Group 11: Handling difficulty & Skills for design	0.272

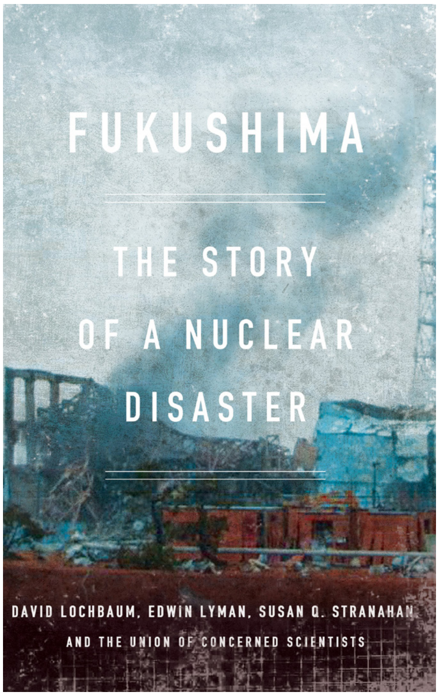
Book Review

By Mark L. Maiello
Book Review Editor

Fukushima: The Story of a Nuclear Disaster
David Lochbaum, Edwin Lyman, Susan Q. Stranahan, and the Union of Concerned Scientists

Hardcover, 310 pages
ISBN 978-1-59558-908-8
The New Press, 2014

Disclosure: the book reviewer, Mark L. Maiello, is a member of the Union of Concerned Scientists.



With four years of hindsight to guide them, the authors begin their narrative on that now historic day of March 11, 2011, with a blow-by-blow reenactment of the nuclear crisis at the Fukushima Daiichi Nuclear Power Plant (NPP). Their story arc includes many perspectives ranging from that of heroic plant superintendent Masao Yoshida, who fought valiantly to save the plant while accommodating the constant inquiries of his prime minister, Naoto Kan, to U.S. Nuclear Regulatory (NRC) Commissioner Gregory Jaczko and his boots-on-the-ground subordinates Charles Miller and Jim Trapp, who were attempting to ascertain the situation in the face of Japanese secrecy and intransigence. In the later chapters, the book moves away from the historical account into a discourse contending that a Fukushima-type disaster is possible in the United States, largely due to the effects of regulatory capture of the NRC by the nuclear industry and the manner in which nuclear power self-polices, often taking what are considered expedient steps to head off onerous regulations that the NRC might impose.

The book appears to be well-researched with ten pages of references supported by an eight-page glossary and list of key figures involved in the incident. An appendix concerning itself with the underlying causes of the incident is really there to argue that computer modeling of reactor accidents is inadequate for simulating these complex occurrences. The writing is crisp and largely free of confusion considering the simultaneity of events and the large number of personalities involved.

The initial chapters of the accident are compelling. Indeed, the actual events lend themselves to good storytelling. Of competing interest are the people caught in an intractable situation imposed by nature that went beyond the control of technology to remedy. There are moments when much like the victims of the classic technological disaster involving *RMS Titanic* no solution appears possible because potential strategies were either considered unnecessary *a priori* and therefore were not provided for or were removed from consideration by the consequences of the natural forces involved.

The authors eventually take the discourse to the broader issue of nuclear power safety and its current status in the United States. The prognosis is not good according to their analysis. Fukushima exposed inadequacies that they contend will disappear not by technical solution but only metaphorically, by fading over time in the collective public memory.

The reasoning behind this forecast is partially attributed to the alleged aforementioned regulatory capture by the commercial nuclear industry of their overseer. The industry through its trade associations, such as the Nuclear Energy Institute (NEI), can present solutions for problems before the NRC can demand potentially expensive and/or burdensome regulations. The NRC reviews and can disapprove these procedures of course, but such a relationship falls short of the traditional, effective policing and inspection methods of old in the eyes of the authors. After all, public safety should take precedence over profit, and the protection of profit appears to be a reason that the industry attempts to circumvent the traditional regulatory framework. An example of the alleged deteriorating relationship that the authors provide relates directly to the primary cause of the Fukushima accident: inundation of a NPP by water.

According to the authors, some thirty-four NPPs in the United States can be flooded due to dam failures (or perhaps by weather-related flooding of nearby rivers) with the same catastrophic results as at Fukushima: a "station blackout" leaving the operators with little or eventually no electrical power to run the pumping systems that cool the reactors so as to prevent core meltdowns. The U.S. nuclear industry through the NEI developed a contingency plan whereby electrical generators and other emergency equipment are stored off-site to be transported to the affected NPP post event. The authors' preferred alternative is the construction of "sea walls" of adequate height and strength to keep the flood waters at bay. The NEI ran their "FLEX" plan to the NRC before regulations anticipated in the wake of Fukushima could be put forth. The authors contend that the NRC acceptance of the plan was a triumph of cost savings over public safety. They explain the inadequacies of the plan emphasizing that even after witnessing Fukushima, the industry scripts accident scenarios in a manner that guarantees successful remediation. The reader is left to ponder whether that is true and whether the industry's tactics of getting ahead of the regulator is a valid way to promote public safety.

One of the arguments made in the book is that the philosophy of "defense-in-depth" used by the NRC and the industry worldwide to mitigate accident repercussions was proven by Fukushima to be inadequate. Even a system of deeply embedded multiple backup systems was made to fail, given the correct circumstances. Inadequate statistics (the plant began construction in the 1960s), "predicted" that tsunamis greater than ten feet in height were so improbable that they could be ignored in the plant design. These inadequacies, particularly the reliance on earthquake statistics, the modeling of reactor accidents, and the predictions of radioactive material plume dispersal, are given significant importance by the authors. The concept of the defense-in-depth strategy, if adequately executed, is sound. However, it is subject to review especially if new data such as provided by the evolving science of seismology reveal that modifications to the strategy are in order. Fukushima plant owner TEPCO never fully responded to updated tsunami height predictions, illustrating that institutional inertia can be just as devastating as Mother Nature.

Another story arc of the book is the question of what constitutes adequate protection. When do we say that we are "safe enough"? It is intimately related to the "it can't happen here" philosophy espoused by the domestic nuclear industry and its regulator. These attitudes are the authors' dragons that must be slayed. But death comes slowly or not at all for such institutionalized thinking. The writing team claims that only major reform will derail the regulatory regime from the feedback loop it finds itself in. They argue that the NRC will not take actions that call into question its previous decisions. Essentially, the accusation is that the NRC will not allow itself to be seen as fallible. Contending that the NRC fears alarming the citizenry, the authors claim that significant moves to increase safety provide evidence that safety was, in fact, previously compromised. This, they decide, has caused NRC to make choices that too often align with the desires of its licensees while not fully mending the nuclear safety net. Even the consequences of inadequate planning at Fukushima Daiichi apparently have not changed the thinking at the NRC.

The authors are careful to point out that the NRC technical staff is at times at odds with the NRC commissioners who make the final decisions. The NRC Near-Term Task Force that was formed to analyze whether a Fukushima-like accident could happen in the U.S. apparently called for moderate reforms to the regulatory structure to cover accidents beyond what was studied before March 11, 2011. According to the authors, it called for, among other things, less reliance on industry initiatives and more on a robust program for dealing with the unexpected, severe accident scenario. They report that the recommendation was scuttled by the NRC commissioners.

The issues concerning NRC reform are not easily resolved nor is this book necessarily the place for that. However, it is clear that the authors desire foremost that the NRC reestablish its primacy in the regulator/licensee relationship and that the licensees expend their money to adequately protect their plants against station blackouts. The industry may believe it has done so and with NRC approval, but not so the authors who put public safety on the highest of all pedestals.

In general, the authors' claims do not read as exaggerated or unreasonable and appear to be based in fact. On rare occasion, in particular concerning decisions made to mitigate the incident or later in reference to NRC oversight of the industry, their tone veers toward the mildly sarcastic. This is somewhat unhelpful. Objectivity and admittedly a blander narrative, lend themselves to an atmosphere of impartiality and a scientific viewpoint that readers with a technical background would likely prefer. Derision, however mild, speaks to some readers negatively, especially on a topic as polarizing as nuclear power.

The point of the book is succinctly summed up in its final chapter. The writers assert that the Fukushima Daiichi NPP accident should not have come as a surprise. As unlikely as it was, it came to fruition as a result of an initial improper assessment of nature's power that was not effectively acted upon while coupled to an inadequate collaboration between government oversight and industry operations. Further, it was also partially due to shortsightedness concerning the price society would have to pay if catastrophe struck. It was not considered that the upfront costs for excellence in engineering and safety would be much less than the remediation of 1,500 square miles of contaminated property and the plant itself. We are reminded that to prevent another such accident, wholesale regulatory and safety changes are needed not only abroad but here in the U.S. as well.

This book is an intellectually healthy read for one particular reason. A book such as this, when presented with an honest factual foundation, asks questions that periodically need to be raised to test the status quo. Books like this keep us honest. They ask hard-to-answer questions and raise concerns that periodically need to be addressed. Even if this reviewer is as much at the mercy of the authors as most other readers when it comes to evaluating the assertions made, one observation that the writers pass down to us is difficult to disagree with: The nuclear industry has had its share of heroes from previous accidents and at Fukushima as well. It does not need any more.

Erratum

A History of U.S. Nuclear Testing and Its Influence on Nuclear Thought, 1945-1963, is a single volume and not two volumes as indicated in the title section of the review that appeared in Volume 43, No. 1. We regret the error.

Suggest a Book

Is there a book you would like to see reviewed in *JNMM*? Send the book title and author name to psullivan@inmm.org. Books must have been published no earlier than 2012 to be considered.

Taking the Long View in a Time of Great Uncertainty

International Collaborations Amid a 21st Century Test for Diplomacy

By Jack Jekowski
Industry News Editor and Chair of the Strategic Planning Committee
Contributors: Mike Whitaker, Susan Pepper, and Kim Gilligan

Figure 1

Figure 2

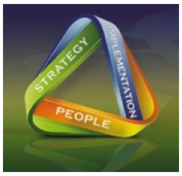
At the Institute's 55th Annual Meeting in Atlanta in July 2014, we had an extraordinary second plenary session on Tuesday that included a presentation by Tero Varjoranta, International Atomic Energy Agency (IAEA) Deputy Director General and Head of the Department of Safeguards (Figure 1). Only two days after the IAEA had provided confirmation to the P5+1 (or E3+3, as it is called in some venues)[1] that Iran had implemented all of the voluntary measures it had agreed to under the Joint Plan of Action,[2] Tero spoke about the need to further optimize the productivity of the Agency as it faces an ever-increasing international workload, and new challenges with the advancement of technologies and increasingly complex diplomatic efforts to resolve issues in a world where more nuclear facilities and material is coming under IAEA safeguards. The interrelationship of diplomatic efforts to resolve the Iranian situation and the technical capabilities of the IAEA to provide verifiable information to support those efforts is an amazing success story of diplomacy in the 21st Century. Following his plenary presentation, a special panel discussion titled "*How the Evolving Domestic, Regional and IAEA Safeguards Requirements and Practices are Influencing Safeguards Implementation and Culture" was* emceed by INMM International Safeguards Division (ISD) Chair, Mike Whitaker[3] (Figure 2). The presentation and discussions were enlightening, and revealing, as the enormity of the work that the IAEA[4] has been successfully doing internationally was described in the context of limited resources and funding available for the growth in their mission (one comparison made was to the equivalent budget of the Boston Police Department). The invited guests also described the diversity of technical challenges that are encountered as well as some of the international political environments in which they have to operate.

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

INMM's Long-Standing Relationship with the IAEA

INMM has had a close relationship with the IAEA over the decades, with many interchanges going on between the organizations in terms of people, processes, technologies and policies. Most recently, several INMM members, including members of the Executive Committee, attended the 2014 Symposium on Safeguards, organized in cooperation with the INMM and the European Safeguards Research and Development Association (ESARDA).[5] With a theme of "Linking Strategy, Implementation and People," this Symposium provided an opportunity for the Institute to strengthen our international collaborations, with incoming President Larry Satkowiak sharing the podium with an array of internationally renowned experts in nuclear policy and technology. Mike Whitaker, Susan Pepper, and Kim Gilligan, who also attended the Symposium, worked with the Symposium organizers and the rapporteur, Karen Owen-Whitred, to summarize the themes that emerged from the Symposium's sessions. Owen-Whitred presented a summary during the Symposium's closing plenary and a digest of her remarks is presented below. While these technical and policy exchanges on nuclear verification were underway in Vienna, there were also extraordinary diplomatic discussions occurring in many global venues among the P5+1 to work toward a solution to the Iranian nuclear issue.

Linking Strategy, Implementation and People



The IAEA's Symposium on Safeguards was held October 20-24, 2014, at the Vienna International Centre in Vienna, Austria. The Symposium was organized around five concurrent sessions, covering more than 300 papers and presentations. These sessions were complemented by exhibits put on by vendors, universities, ESARDA, INMM, and member state support programs (MSSPs). There were also e-posters, where the authors invited the audience to visit a video display for a more personalized presentation, and technology demonstrations. Representatives of fifty-nine member states participated in the Symposium.

Owen-Whitred, director of the International Safeguards Division with the Canadian Nuclear Safety Commission, worked with a team of IAEA and member state representatives to pull together highlights of the Symposium, and, in her remarks, she provided her thoughts on some of the themes that she saw emerge over the course of the week.

The three official themes of the Symposium were strategy, implementation, and people. In her remarks, Owen-Whitred focused on the *intersections* among them. She used the concept of linkages as a useful *lens* through which to highlight some specific *content* of the Symposium.

She framed the first connection, strategy and implementation, as the intersection between *ideas* and *action*. A session focused on the Safeguards Implementation Practice Guides, or SIP Guides, which have been developed through collaboration between the IAEA and professionals from several member states. The guides help states understand the legal text and requirements of safeguards, to help them move from concepts to good practices, and they include powerful examples to add clarity. The success of this project demonstrates the natural and *vital* connection between strategy and implementation.

The second linkage between implementation and people can be thought of in terms of "on the ground" activities and was addressed in many of the more technical sessions. It represents the practical, concrete techniques and tools being put in the hands of the people to perform work. The related sessions ranged from communication technology to measurement techniques to analytical methodology and stimulated very lively discussions, demonstrating both the knowledge level of the Symposium participants and their engagement with "practical safeguards." These sessions also highlighted the collaborative nature of much of the ongoing technical work. In addition to the more highly technical work, the link between *implementation* and *people* is also about getting *practical* experience. Finally, it was clear that the advanced technologies that are being developed still often require a skilled human to interpret the data.

The final linkage between *people* and *strategy* is about mobilizing people in pursuit of an organization's strategic goals. A key message coming out of the session on Performance Management was the importance of clearly and transparently reporting results. This applies to all safeguards stakeholders in their respective organizations; operators, regulators, and the Agency all need to be confident that the safeguards community is fulfilling its goals. We are all striving to do a good job, but we can't forget the importance of *demonstrating* that we're doing a good job.

Owen-Whitred then spoke about the overarching themes that emerged during the Symposium. The need to develop the next generation of safeguards experts emerged during the opening plenary and was repeated often. The twin realities of a large group of experienced staff nearing retirement and the need for highly skilled and motivated newer staff highlight the importance of knowledge retention, knowledge transfer, and training. All of us in our respective organizations must put in the sincere effort to find them, train them, and strive to *motivate* and *inspire* them so that they will have both the *abilities* and the *desire* to contribute to the field of safeguards.

Some presentations and posters touched on innovation in technology and methodology. Speakers noted the importance of being able to use emerging technologies from non-safeguards disciplines and the value of MSSPs in advancing R&D. There were a number of projects or technologies presented that are still in the early, or even conceptual, stages of development; others pointed to challenges that require more work, such as spent fuel verification, UF_6 cylinder tracking, and the digitization of site maps and State declarations in general.

There were three separate sessions

dedicated to IAEA-state cooperation, and the concepts of partnership, joint endeavors, and collaboration ran through many of the technical and policy sessions. The importance of close cooperation within the safeguards community was discussed in sessions as diverse as advanced communication technology, instrumentation data analysis, and evolving safeguards implementation. This theme goes hand in hand with one of open and clear communication—this links to the importance of clearly defining the roles and responsibilities of all parties involved in implementing safeguards, and the value of proactive communication in managing day-to-day safeguards issues. There were many examples of safeguards cooperation around the world.

In closing, Owen-Whitred told the audience there is an opportunity for further discussion on the role of the operator, a stakeholder who is usually underrepresented at safeguards meetings. In the lead up to the next Symposium, we should all consider how we can seek to more meaningfully engage operators in safeguards discussions. She closed her remarks with an acknowledgment that the collaboration and communication facilitated by the Symposium was not meant to end. The links that were made during the Symposium should be kept alive.

The 21st Century Test for Diplomacy and the Critical Role for the IAEA and INMM

Without the "technical backup" provided by organizations like the IAEA, INMM, WINS, and others, the diplomatic efforts we are witnessing in real time to address the Iranian nuclear issue would be much more difficult, if not impossible. Verification of agreements using the technical knowledge, expertise, and equipment that is the basis of the nuclear materials management discipline is a critical element to the successful accomplishment of negotiated settlements in this complex environment. In previous columns[6], I have spoken of the "sea change" that has occurred in the U.S. National Security Strategy (NSS) during the Obama Administration, elevating diplomatic efforts to the same level of importance as military response. So important has this aspect of the reshaping of the U.S. NSS been in the context of the current situation with Iran and the role of the IAEA and partner institutions such as the INMM, that, whether planned or not, Iran has become the litmus test for this policy. The entire world is watching. It is up to all of us to do what we can in our spheres of expertise to provide the "backup" that is needed for the diplomats to accomplish their mission. It is through the international dialogues and collaborations that we have witnessed this past year, including the IAEA Safeguards Symposium and the INNM Annual Meeting, that we might hope to see a turnaround toward a safer and saner world.

Endnotes

1. The P5+1 is a moniker given in 2006 to the five permanent members of the U.N. Security Council, the United States, Russia, the United Kingdom, France, and China, who are also recognized as the Nuclear Weapons States (NWS) under the Nuclear Nonproliferation Treaty (NPT), and Germany, as they joined efforts to work toward a diplomatic solution with Iran to resolve concerns over the intentions of its nuclear program. The United Kingdom, France, and Germany had previously been known as the EU3 or, simply, E3, leading to the alternate moniker for the P5+1 of E3+3.
2. The Joint Plan of Action was an agreement signed by the P5+1 and Iran on November 24, 2013, and then extended on July 20, 2014, and once again extended on November 24, 2014. For an extensive timeline of actions planned and accomplished, see http://www.armscontrol.org/Implementation-of-the-Joint-Plan-of-Action-At-A-Glance
3. Participants included Piotr Szymanski, director of Nuclear Safeguards, European Commission; Sonia Fernandez-Moreno, Brazil-Argentine Agency for Accounting and Control of Nuclear Materials (ABACC); Steve Adams, deputy director of the U.S. Department of State's Office of Multilateral Nuclear and Security Affairs; Olli Heinonen, former IAEA inspector and now senior fellow at the Harvard Belfer Center; Larua Rockwood, senior research fellow, Harvard Belfer Center. Also see http://www.inmm.org/Opening_Plenary_Speaker.htm
4. See http://www.iaea.org/.
5. See http://www.iaea.org/safeguards/symposium/2014/home/index.html for more information about the conference held October 20-24, 2014, and https://esarda.jrc.ec.europa.eu/ for more information on ESARDA.
6. Jekowski, J. 2013. "Taking the Long View in a Time of Great Uncertainty: As the World Turns... Toward a More Dangerous Place." *Journal of Nuclear Materials Management*, Volume 40, No. 4, 111-113.

Calendar

March 17–18, 2015
INMM Reducing the Risk Workshop
George Washington University
Elliot School of International Affairs
Washington, DC USA

April 26, 2015
INMM/ANS Workshop on Safety-Security Risk-Informed Decision-Making
Sun Valley Resort
Sun Valley, Idaho USA

July 12–16, 2015
INMM 56th Annual Meeting
Renaissance Esmeralda
Indian Wells, California USA

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

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

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

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

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