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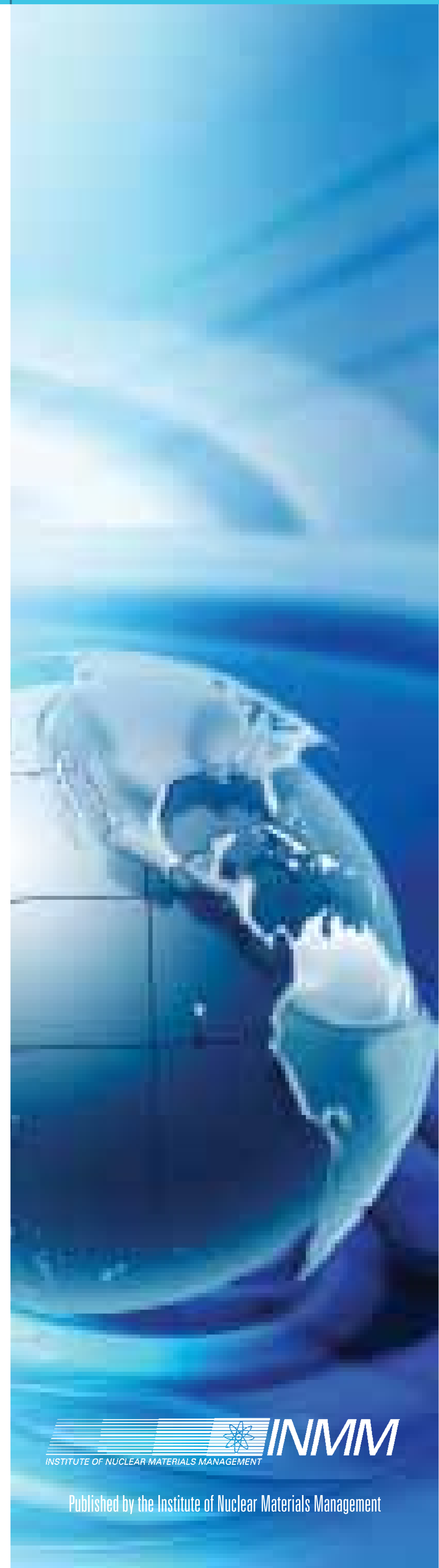

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JNMM Journal of Nuclear Materials Management

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Congratulations to *JNMM* on 40 Years of Publishing

By Scott Vance
INMM President

How is it possible that 2011 is "so yesterday"? Even though those of us who work in government are given a preview of the coming year end three months before the calendar indicates it is over, I am nonetheless amazed that once again it is time to change the last digits of the date I write on documents. And as I begin to write "12" instead of "11," I am reminded that another milestone for INMM is upon us.

This year marks the fortieth anniversary of the premier publication in nuclear materials management, the *Journal of Nuclear Materials Management.* The first issue was published on April 1, 1972 (no fooling), and contained two articles: *Control of Materials in Research: A Special Management Problem,* and *Design and Operation of a Plutonium Laboratory.* Both articles were submitted by authors from Oak Ridge National Laboratory. Forty years later, INMM is proud to continue to have a strong representation from Oak Ridge, as well as strong participation from the other U.S. Department of Energy laboratories. Even more significantly, INMM also now has strong participation from, and *JNMM* regularly publishes articles submitted by research laboratories from around the globe. The global exchange of "lessons learned" and "best practices" in the management of nuclear materials was the goal of publishing the *Journal* from the beginning, and reaching the fortieth year of that mission is an accomplishment that should make all INMM members proud.

Unfortunately, many individuals who would benefit from the information contained in the *Journal* do not know of its existence, even after forty years. As an organization, we have consciously decided to limit the distribution of the *Journal* as a benefit to membership, rather than a publication that is widely distributed to those that might be interested. Not only does this significantly reduce our expenses, but it adds another incentive for individuals to become active members. Consequently, we find that young professionals or others interested in the type of information contained in the *JNMM* often are not exposed to the publication. We have taken a positive step to change that recently by contracting with a technical "search engine" so that *JNMM* articles appear when a relevant online search is performed. We hope that this increases the public exposure of the excellent information that is regularly published. However, the best way to expose interested individuals to this information is much easier—each of you works with other individuals who are also involved in the field of nuclear materials management. I encourage you to distribute your copy of *JNMM* when you receive it to others in your office or workgroup. Their professional curiosity will then lead them to want each new issue as they find information that is useful to them.

The observation that each of us is probably the best advertisement for the *Journal* leads me to another challenge that I hope you will take seriously. While the *Journal* is an excellent resource for those of us working in the nuclear materials management field, preparing the next generation to take up the reigns of this profession will require more than just a *JNMM* subscription. We all need to ensure that we are passing on the "corporate knowledge" that has been generated over the last half century.

INMM is proud of the increased participation by young professionals over the past five years. Each year, the number of student memberships and attendance at the Annual Meeting continues to increase. Again, however, the best person to pass on the information that you have gained over your professional career is you. No one understands the insights that you have gained and the progress that your professional efforts have made better than you. While the goal of the Annual Meetings and the *Journal* is to allow professionals like you to share your knowledge with other members, it is extremely important that each of us take the opportunity to personally mentor one or two young professionals. If you have not found someone to personally mentor, I encourage you to sign up on the website to be one.

I have previously mentioned that I have a personal interest in exposing many of my colleagues in the legal community to INMM. As I interact with colleagues at various conferences and meetings, I am amazed at the number of legal practitioners working on legal issues related to nuclear materials management who have no idea that we exist. Just as I have challenged you, I recognize my own responsibility in that regard. Recognizing my own bias, I am nonetheless convinced that no one should be working on such issues without the benefit of INMM's collective wisdom. So, I will continue to pursue opportunities to bring about this exposure to individuals whom I interact with; I hope that you will do the same.

INMM President Scott Vance may be reached via e-mail at savance@tva.gov.

Special Issue from RAP-NIS Students

By Dennis Mangan
INMM Technical Editor

The first four articles in this issue of the *Journal* were produced by students under the Russian Academic Program for Nonproliferation and International Security (RAP-NIS) sponsored by the U.S. Department of Energy's National Nuclear Security Agency's Offices of Defense Nuclear Nonproliferation and Nonproliferation and International Security. This program is managed by the University Research Alliance at Texas A and M University (TAMU). RAP-NIS is a collaborative effort between TAMU, the Russian National Research Nuclear University Moscow Engineering and Physics Institute (NRNU-MEPhI), and the Obninsk State Technical University's Institute of Nuclear Power Engineering (NRNU-IATE). Claudio Gariazzo, a research engineer in the Nuclear Security Science and Policy Institute at TAMU was instrumental in arranging for these articles to be published in this issue of *JNMM*.

Gariazzo wrote: "The RAP-NIS' mission is to educate graduate students in the three universities' respective nuclear engineering programs in the areas of nuclear nonproliferation and safeguards. Relying on strong inroads between these three universities, the faculty and staff have jointly developed courses in nuclear material safeguards and nonproliferation issues and have guided student research projects in order to provide students the opportunity to apply their education. Among the three institutions, five masters of science programs have been created, fifty-two courses have been developed with more than 3,800 students having taken the courses, and eighty students have graduated from the respective programs. Twenty-six directly sponsored theses/dissertations have been produced by graduates. In addition, students in the program are provided the opportunity to visit international nuclear fuel cycle facilities and discuss applied safeguards measures with facility operators, grow their personal professional networks with professionals and students from other countries, and expand their understanding and appreciation of safeguards culture.

"The four articles included herein represent the quality of work by graduates of the program from the United States and Russia. … The authors have gained expertise in their respective research areas and have since begun careers at the Kurchatov Institute of Russia, Chalmers University of Technology in Sweden, and the Pacific Northwest National Laboratory in the United States. … The four articles presented in this issue of the *JNMM* exhibit the commitment by TAMU, NRNU-MEPhI, and NRNU-IATE in producing the next generation of nuclear safeguards experts that is needed in Russia and the United States."

Our thanks to Gariazzo for his efforts.

In their article, *MCNPX-PoliMi Post-processing Algorithm for Detector Response Simulations,* Sara Pozzi, INMM Member-at-Large, and her coauthors discuss a post processor for a Monte Carlo code used in analyzing a detector's response, which can enhance the output of the code to achieve a more realistic prediction of the response.

In *Roles for Process Monitoring in Nuclear Safeguards at Aqueous Reprocessing Plants,* fourteen co-authors join their experiences with safeguards as practiced by the International Atomic Energy Agency, nuclear material accountancy, containment and surveillance, material balance, large aqueous reprocessing plants, process monitoring, and perhaps many more areas of expertise, to consider how process monitoring might be used in conjunction with nuclear material accountancy and containment and surveillance to enhance the effectiveness of safeguarding a large aqueous reprocessing plant.

Mona Dreicer, also an Member-at-Large, and her co-authors, report on the INMM Workshop, *Preparing for Nuclear Arms Reductions to Address Technical Transparency and Verification Challenges.* According to the report, this workshop addressed key issues that can arise when nuclear weapon states interface with non-nuclear weapons states in addressing treaty verification, particularly if the verification involves eliminating all nuclear weapons.

Industry News Editor Jack Jekowski and INMM Vice President Ken Sorenson summarize a successful INMM/ESARDA (European Safeguards Research and Development Association) workshop, *Future Directions for Nuclear Safeguards and Verification,* assisted in by Jim Larrimore, chair of the INMM International Safeguards Technical Division, and Michel Richard of ESARDA.

We have two book reviews, one by Mark Maiello, who provides a review of Michael E. O'Hanlon's book, *A Skeptic's Case for Nuclear Disarmament,* and one by Walter Kane, *Fuel Cycle to Nowhere: U.S. Law and Policy on Nuclear Waste,* authored by Richard and Jane Stewart. Both appear to be interesting reading.

We close with *JNMM's* 40th anniversary by republishing a 1976 article by R. Auguston, D. Reilly, and T. Canada of the U.S. Los Alamos Scientific Laboratory, *The LASL-U.S. ERDA NDA Training Program,* published in Volume 5, No. 1. This paper illustrates how things have changed and yet stayed the same. Los Alamos Scientific Laboratory (LASL) and the Energy Research and Development Administration (ERDA) have changed names to Los Alamos National Laboratory (LANL) and the U.S. Department of Energy (DOE). Yet their missions remain much the same. We also wish to recognize the many contributions to the *Journal* from Doug Reilly. Including this paper, he has been an author and co-author of papers to the *Journal* spanning more than three decades. His name however hasn't changed and neither has his mission.

Multi-attribute Evaluation and Choice of Alternatives for Surplus Weapons-grade Plutonium Disposition Using Utility Function at Functional Dependence of Weighting Factors

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Abstract

Among the major problems of nuclear power are the problems of recycling, safe long-term storage, and the management of nuclear materials. The greatest concern is caused by significant stocks of weapons-grade plutonium, where choosing the method of its disposition can be formalized as a multi-attribute problem of selecting one of thirteen possible alternatives.

One of the main goals of the multi-attribute utility function analysis is the investigation of the different combinations of assumptions and performance weights for the purpose of ranking. An additive multi-attribute utility model is most often used in practice, and weights are initially assumed to be constants. In some cases, it may be appropriate to have weights depending on the attribute satisfaction performance value.

Investigations of several versions of weighting functions for evaluating and choosing alternatives for the surplus weapons-grade plutonium disposition were performed.

A sensitivity analysis was performed to explore the robustness of the rankings relative to changes in the weights in more detail. This series of sensitivity analyses indicated that the ranking of the alternatives is relatively insensitive to changes in the weighting factors over reasonable ranges.

Using weighting functions enlarges the possibilities of the multi-attribute evaluation, making it possible to consider, for example, decision-maker preferences for different alternatives.

Introduction

Progress of the Russian-American efforts in reducing strategic nuclear arms has put safe disposition of highly enriched plutonium on the agenda of nuclear nonproliferation. The issue of recycling weapons-grade plutonium is most relevant today and attracts the attentions of politicians, scientists, and engineers in Russia and abroad. The main objective is to prevent the proliferation of nuclear weapons while providing efficient plutonium storage and the safety of man and the environment.

Utility Function for Solution of Multi-Attribute Problems

The problem of the disposition of surplus plutonium can be formalized as a multi-attribute problem with a choice of alternatives from a set of thirteen. The theory of multi-attribute utility function is one of the main analytical instruments within the field of decision analysis. Data analysis made by use of a multi-attribute utility function lets us identify goals for evaluating alternatives for the disposition of surplus weapons-grade plutonium. It is also possible to find those alternatives that are the best for most of the goals, and the most important.

When considering alternatives, importance or weight of factors is used. The importance determines the relative preference of the alternative for each target. Differences in the expert judgments and estimates by different methods may lead to differences in weights that, in turn, complicate the task of identifying the best choice of a set of given alternatives. An analysis of the multi-attribute utility function provides ranking of the alternatives for a given set of facts or suppositions, and allows weight estimations.

Multi-attribute utility function analysis enables us to investigate the different combinations of assumptions and attribute weights for the purpose of ranking. This approach assumes the realization of four actions:

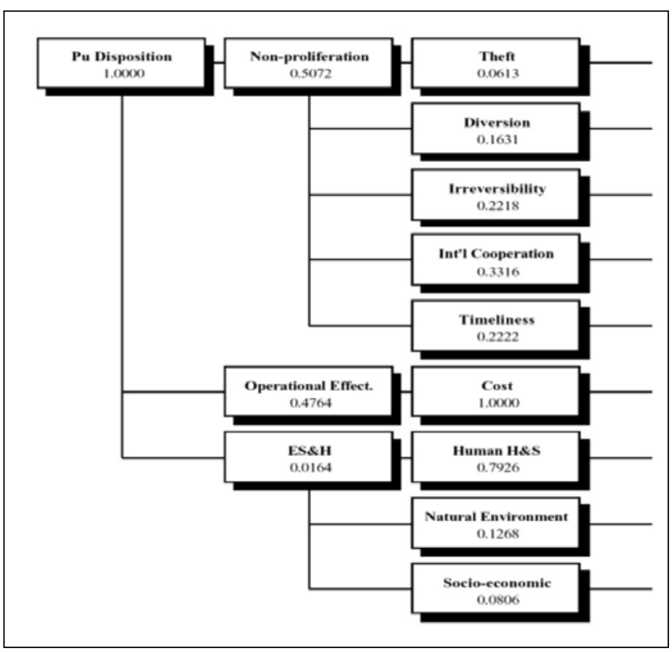
- The development of alternatives and evaluation criteria;
- The numerical estimation of these criteria values and their importance or weighting factors;
- Estimating the alternatives, with respect to the criteria; and
- Conducting a sensitivity analysis of the final chosen alternative.

The goals or objectives included in the multi-attribute utility (MAU) model are derived from criteria developed in the screening process.[1] In the MAU model, they are arranged in a hierarchy. This hierarchical structure was chosen to facilitate the specification of a value model. This hierarchy emphasizes three major objectives for the plutonium disposition effort, which are labeled Nonproliferation; Operational Effectiveness; and Environment, Safety, and Health (ES&H), respectively.

The items, shown in Figure 1, deal with the plutonium disposition.[1] Weighted scores are presented for objectives based on the estimates of experts. For instance, the nonproliferation objective is further subdivided into five sub-objectives (criteria): **Theft** (minimizing the opportunities for theft of the materials by unauthorized parties), **Diversion** (maximizing the resistance of the disposition alternative to the diversion of the plutonium by the host nation during processing, and providing an internationally verifiable and acceptable process), **Irreversibility** (maximizing the difficulty of recovering the material after disposition has been completed), **International Cooperation** (fostering international cooperation with U.S. disarmament and nuclear nonproliferation efforts), and **Timeliness** (minimizing the time required for the disposition effort to begin and for the mission to complete).

Each sub-objective on the right-hand side of the figure might be further specified in terms of one or more of thirty-seven measures that are included in the model (e.g., Life-cycle Costs, Time to Start, Material Form). Scores of an alternative on these measures determine to what extent implementation of the alternative would satisfy the objectives. Scores for individual measures are weighted and summed to generate a composite score that reflects the overall desirability of the alternative.[1]

Figure 1. High-level objectives and weights for the plutonium disposition



The U.S. Department of Energy (DOE) Office of Fissile Materials Disposition has announced a Record of Decision selecting alternatives for disposing of surplus plutonium. Thirteen alternatives for disposition of surplus weapons-usable plutonium are considered in the report,[1] they are: Reactor, Immobilization, and Direct Disposal. The five Reactor alternatives envisage surplus weapons-usable plutonium be used for production of mixed oxide (MOX) fuel for nuclear reactors:

1. Existing Light Water Reactors, Existing Facilities (A MOX fuel fabrication plant would be built in an existing building at a DOE site, the MOX fuel being irradiated in existing private sector commercial reactors).
2. Partially Completed Light Water Reactors (Commercial LWRs, on which construction had been halted, would be completed and operated by DOE).
3. Existing Light Water Reactors, Greenfield Facilities (A new co-located pit disassembly and conversion and MOX fuel fabrication facility would be built at a DOE site, with MOX fuel irradiated in existing privately-owned commercial reactors).
4. Evolutionary Light Water Reactors (New LWRs would be built and operated by DOE).
5. CANDU Reactors (MOX fuel fabricated at a U.S. facility would be transported to one or more Canadian commercial heavy water reactors and irradiated).

Another six alternatives evaluate different ways to immobilize surplus plutonium with radioactive glass-bonded zeolite, or mix with borosilicate glass, ceramic and radioactive materials:

6. Vitrification Greenfield (Surplus plutonium would be mixed with glass and radioactive materials at a new facility to form homogeneous borosilicate glass logs).
7. Vitrification Can-in-Canister (Surplus plutonium would be mixed with non-radioactive glass and poured into small cans. These small cans would be placed in larger canisters, which are then filled with radioactive waste glass).
8. Vitrification in an Adjunct Melter (Surplus plutonium would be mixed with glass and radioactive materials in a supplemental melter facility to form homogeneous borosilicate glass logs).
9. Ceramic Greenfield (Surplus plutonium would be mixed with ceramic and radioactive materials at a new facility to form homogeneous ceramic disks. These disks would be placed in large canisters).
10. Ceramic Can-in-Canister (Surplus plutonium would be mixed with non-radioactive ceramic materials to form ceramic pellets. These pellets would be placed in larger canisters filled with radioactive waste glass).
11. Electrometallurgical Treatment (Surplus plutonium would be immobilized with radioactive glass-bonded zeolite).

The last two alternatives present plutonium pellets immobilized with ceramic and placed in a borehole. These involve using an inert matrix or direct emplacement in a deep borehole):

12. Deep Borehole (Direct Emplacement) (Surplus plutonium would be converted to a suitable form and placed in a deep borehole).
13. Deep Borehole (Immobilization) (Surplus plutonium would be immobilized with ceramic pellets and placed in a borehole).

Because the decision for plutonium disposition involves multiple criteria, it is appropriate to use the multi-attribute utility model for this study. It is based on the calculation of a multi-attribute utility function $u(x_1, x_2, \ldots, x_n)$, where x_i represents the level of performance on sub-objective or measure *i*.[2] The utility function might be additive, multiplicative, or another form to simplify assessment.

The most commonly used model is the additive multi-attribute utility model that is represented as follows:

$$u(x_1, x_2, \ldots, x_n) = \sum_{i=1}^{n} w_i u_i(x_i) \qquad (1)$$

where $u_i(x_i)$ is a single-attribute value function over sub-objective *i*, which is scaled from 0 to 1, and w_i is the weight for sub-objective i and $\Sigma_{i=1}^{n} w_i = 1$.

In some practice cases it is pertinent to have the weights dependent on the satisfaction degrees of the various attributes (criteria).[3]

The idea of considering weighting functions that depend continuously on attribute satisfaction values (i.e., good or bad attribute performances) is supported by common sense reasoning and experience in the context of decision theory. In fact, it is not difficult to think of plausible decisional problems in which weights should, to some extent, depend on the corresponding attribute satisfaction values.

From the perspective of a decision maker, when considering an alternative, the weight of an important attribute with a low satisfaction value should in some cases be penalized, in order to render the given attribute less significant in the overall evaluation of that alternative. Accordingly, when considering two alternatives, the dominance effect in one important attribute would become less significant when the attribute satisfaction values are low. In the same spirit, the weight of a less important attribute with higher satisfaction values should in some cases be rewarded, thereby rendering more significant the dominance effect in that attribute. Summarizing, in some cases it may be appropriate to have weights depending on the attribute satisfaction values.[3]

We assume that the attribute satisfaction values are in the unit interval [0,1], and we consider the weighting functions $w_i(x)$ generated by the n functions $f_k(x_k)$ are defined as:

$$w_i(\boldsymbol{x}) = f_i(x_i) / \sum_{k=1}^{n} f_k(x_k). \qquad (2)$$

The positive weighting functions $w_i(x) > 0$ satisfy the normalization condition $\Sigma_{k=1}^{n} w_k(x) = 1$.

Results of Applying Weighing Function, Depending on Criterion Value x_i

Investigations of several versions of weighting functions were carried out. The five criteria (sub-objective categories) mentioned above are considered for nonproliferation objective. Input single-attribute values are taken from Reference 1.

Table 1 shows correspondence of alternatives to their ranks for four types of weighting functions: $f(x)=(x+1)/2$, $f(x)=x$, $f(x)=x^2$, $f(x)=x^3$. Similar data, received in 1 for w_i presented in Figure 1 are also given in Table 1. Alternatives are placed according to their ranks (a lesser rank corresponds to a greater alternative value; therefore, the alternative with the greatest value has a rank equal to 1 and appears to be preferable).

Table 1. Correspondence of alternatives to their ranks

Rank	(x+1)/2	x	x^2	x^3	Data [1]
1	13	13	13	13	13
2	7	7	10	10	10
3	10	10	7	7	7
4	1	1	1	1	1
5	12	5	5	5	5
6	5	8	6	6	12
7	9	9	8	8	9
8	8	6	9	9	8
9	6	12	2	4	6
10	2	2	11	3	2
11	11	11	4	2	3
12	3	3	3	11	4
13	4	4	12	12	11
$\sum \delta^2$	**8**	**22**	**72**	**75**	

The Table 1 results show that the calculated ranks of alternatives coincide with the data in 1 and the greatest degree of affinity to the ranks of alternatives in 1 is provided by weighing function $f(x)=(x+1)/2$ and the lowest is $f(x)=x^3$; weighting functions $f(x)=x$ *and* $f(x)=x^2$ provide intermediate values of affinity. For all four kinds of weighting functions, the thirteenth alternative is preferable (deep borehole immobilization). The second rank for linear weighting functions has the seventh alternative (vitrification can-in-can) and the tenth alternative (ceramic can-in-can).

Sensitivity Analysis

The base case analysis should be tested to see if the evaluation of alternatives is robust. This sensitivity analysis consists of making changes in the weights of the five sub-objectives, and observing changes in the resulting evaluations and rankings. The first form of sensitivity analysis is to change the weight of an important sub-objective while leaving the ratios between weights on other sub-objectives unchanged. This will highlight the effect of changing the emphasis placed on an objective. In an evaluation of alternatives for a government agency, this approach to sensitivity analysis is particularly important, since different stakeholders may have very different values that would be expressed through different tradeoffs, and these different tradeoffs would lead to different weights on the sub-objectives and measures.

As an example, results of calculations for the case of varying weighting coefficient w_3 (Irreversibility) are given below in Table 2. By varying coefficient w_3 from 0 to 1, we receive the value of other coefficients.

In this case the relationship between weighting coefficients is as follows:

$$\begin{cases} w_1+w_2+w_3+w_4+w_5=1 \\ w_1/w_2=b_1 \\ w_2/w_4=b_2 \\ w_4/w_5=b_3 \end{cases} \quad (3)$$

where b_1, b_2, and b_3 are constants.

Table 2 shows the results of calculations obtained for weighting function $f(x)=(x+1)/2$.

Table 2. Results of ranking for sensitivity analysis (variation of w_3)

Alternative	Best Rank	Worst Rank	Mean Rank
1	4	4	4
2	10	11	10.44
3	11	12	11.44
4	12	13	12.44
5	5	6	5.22
6	8	9	8.33
7	1	2	1.78
8	7	8	7.67
9	6	7	6.33
10	2	3	2.78
11	9	10	9.33
12	5	13	10.11
13	1	3	1.44

An analysis of the results shows the stability of the alternatives rankings for a wide range of changing w_i.

Perhaps it is also useful to explore the results of changing all of the weights simultaneously, in order to explore the robustness of the rankings of the alternatives in more detail. However, it would be extremely tedious to try to explore all reasonable combinations of values for the weights one at a time. As an alternative to changing weights one at a time, weights have been selected at random using a simple computer simulation program so that the results of many combinations of weights can be explored in an efficient manner. In addition, this simulation study provides a convenient means of testing the robustness of the results of our model.

This second form of sensitivity analysis, based on random weights, was also performed. The results of the sensitivity analyses using this approach are presented in Table 3.

Table 3. Results of ranking for sensitivity analysis (random weights)

Alternative	Quantity of 1st Places	Mean Rank	Final Rank
1	454	6.19	4
2	123	8.26	10
3	117	8.47	11
4	107	8.52	12
5	248	7.26	5
6	184	7.4	8
7	988	5.32	2
8	178	7.47	9
9	195	7.34	6
10	939	5.38	3
11	194	7.69	7
12	28	6.6	13
13	1065	5.11	1

Each simulation study is based on 5,000 iterations (sets). For each iteration, a complete set of weights for the sub-objectives is selected, the scores are aggregated for the alternatives using these weights, and the ranking of each alternative is recorded. The third column in the table presents the mean ranks for all 5,000 iterations. The last column in the table provides the final rank.

When the selection of the weights is completely random, every alternative ranked in the first place for at least twenty-eight of the 5,000 sets of weights generated. This result is not surprising, since none of the alternatives is completely dominated.

With 5,000 randomly generated sets of weights, a relatively greater weight is likely to be generated on one or more sub-objectives in which each alternative performs relatively well. Likewise, a greater weight will be generated for the sub-objective or sub-objectives on which an alternative does not score well, leading to low rankings like in 1. For the random weights, the mean and final ranks are perhaps more meaningful.

Alternatives that rank high on these sub-objectives would tend to be those that perform well on a majority of the performance sub-objectives. The Deep Borehole Immobilization alternative (13) has the best mean rank. The Vitrification Can-in-Can (7), Ceramic Can-in-Can (10), and Existing Facilities (1) alternatives also score well with random weights, while the Ceramic Greenfield (9) and Vitrification Greenfield (6) alternatives appear to be inferior. In fact, there was a very small number of combinations of weights generated (28, 107, and 117 of 5,000 sets of weights) which lead to the Deep Borehole (12), Evolutionary LWR (4), or Greenfield Facilities (3) alternative being the most preferred.

Conclusions

Our investigations permit us to conclude that the use of weighting coefficients estimated with the generating weighting functions for the ranking alternatives enlarges the possibilities of the method of the multi-attribute evaluation, making it possible to consider, for example, decision-maker preferences for different alternatives.

In this paper we investigate four different ways in which the weights can depend on the satisfaction degrees of the various attributes (criteria). We have proposed and discussed two kinds of linear, quadratic, and cubic weight generating functions that penalize poorly satisfied attributes and reward well satisfied attributes.

We have used the weighting functions behavior to Multi-attribute Evaluation and Choice of Alternatives for the Surplus Weapons-Grade Plutonium Disposition and compared the results with the classical weighted average scheme. The approach proposed in this paper shows clearly a richer range of possible aggregation schemes in which the weights take into account the attribute satisfaction values of the various attributes.

A series of sensitivity analyses indicate that the ranking of the alternatives using weighting functions for the aggregation of criteria is steady.

Sensitivity analyses also indicate that the ranking of the alternatives that was determined using the base case tradeoffs and assumptions is relatively insensitive to changes in these assumptions over reasonable ranges. Among the reactor alternatives, the Existing LWR, Existing Facilities and the CANDU alternatives are typically rated among the top two or three, and among the immobilization alternatives, the Vitrification and Ceramic Can-in-Can alternatives dominate the other alternatives. The sensitivity analysis does provide some additional insights regarding a choice between a reactor and an immobilization alternative.

It is logical to recommend proceeding with the parallel development of the highest ranked immobilization alternatives and the Existing LWR, Existing Facilities Reactor alternative.

However, results show that plutonium disposition alternatives that include different methods of immobilization are the most preferable. The best alternative for disposition is when plutonium is immobilized with ceramic and placed in a borehole. Reactor disposition alternatives are less attractive than the others considered.

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Analysis of ^{235}U, ^{239}Pu, and ^{241}Pu Content in a Spent Fuel Assembly Using Lead Slowing Down Spectrometer and Time Intervals Matrix

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Abstract

Knowledge of the physical parameters of irradiated nuclear fuel is going to be a key issue for the continued and future use of nuclear energy. One of the major characteristics of spent fuel, which plays an important role in international nuclear materials safeguards is the quantity of plutonium (Pu) in wastes. It can be determined through the use of various techniques, one of which is the non-destructive assay (NDA) method of slowing-down time spectrometry in lead where the energy spectrum of neutrons can be represented as being monoenergetic with minor deviation from the peak value in each time moment after a fast neutron pulse. This fact was successfully used in developing several methods of Pu mass determination and confirmed the potential of the Lead Slowing Down Spectrometer (LSDS) to get detailed information about spent fuel.[1,2] A method, presented earlier at the International Conference on Current Problems in Nuclear Physics and Atomic Energy,[3] was based on a matrix of time intervals where large differences in the number of fissions of ^{235}U and ^{239}Pu are observed. This technique allows increasing precision in the Pu evaluation by decreasing the self-shielding effect significantly. As opposed to homogeneous-volume approximations used in our previous research, we describe the detailed Monte Carlo models of real fuel assemblies, as well as the effects of the influence of the scintillation detector to the system in question. Although the proposed method for characterizing spent fuel assemblies has only been studied using Monte Carlo simulations, it was possible to demonstrate the determination of ^{239}Pu using a DT pulsed neutron source, a lead slowing down spectrometer, and fast timing scintillator that is sensitive to both photons and neutrons. Additional information about the system can be obtained from n-γ pulse shape discrimination.

Introduction

In response to the technical policy[4] of the International Atomic Energy Agency (IAEA), numerous techniques to quantify Pu in irradiated reactor fuel assemblies have been developed in the last few years. Most of today's corroborative assay methods provide measurements of Pu content with accuracy of approximately10 percent.[5] This could result in a huge amount of unaccounted Pu in high-volume storage or reprocessing facilities. Amongst the most attractive NDA approaches that may be considered as a replacement of those currently used is the method of slowing-down time spectrometry in lead where neutrons gather into a narrow energy group that shifts toward smaller energies with increasing slowing-down time. This fact was noted in 1944 by Feinberg[6] and soon after this, in 1955,[7] this principle was utilized in neutron spectrometry. Then, the Bergman group built the first experimental lead slowing-down-time spectrometer (LSDS or LS-DTS), which was based on a pulsed neutron generator placed in the center of a large pure lead cube.[7] Further research resulted in an analytical expression between the slowing-down time and the neutron energy that confirmed the potential of LSDS to be used in the spectroscopy field. Initially, LSDS was oriented to the measurements of neutron-induced reaction cross-sections in conventional time-of-flight [TOF] experiments.[8]. Only in 1969, Krinninger applied lead spectrometry to the NDA of fissile materials.[9] The work under development and construction of a lead spectrometer facility for the measurement of light water reactor (LWR) fuel has been carried out within the scope of the Karlsruhe Nuclear Safeguards project.[10,11] The amounts of ^{235}U and ^{239}Pu have been determined with approximately 5 percent accuracy using measurements in two different energy regions, around 0.3 eV and 0.025 eV. More recent investigations, performed in 1993 at Rensselaer Polytechnic Institute (RPI) by Abdurrahman,[12] showed that LSDS is capable of evaluating both the ^{235}U and ^{239}Pu contents with about 2 percent accuracy. For comparison purposes, currently-used burn up monitoring methods can provide estimation of Pu amounts within 10 percent uncertainty.[5] In high-volume storage or reprocessing facilities, this could equate to more than 1,000 kg of Pu mass.[13] It is one of the reasons why the interest in the lead spectrometer as an NDA technique for Pu assay has recently increased and several Monte Carlo studies of LSDS performance have been published[14,15] Even the tomography capabilities of Pu mass determination were shown.[14] It was shown that both axial and radial distributions of nuclear material contents can be measured using a new approach with threshold detectors.[15] To study the internal distribution of fissile content, the authors applied neutron emission tomography (NET), which was based on the fact that all induced fission neutrons in each fuel cell contribute to detection in the surrounding detectors over the (1 keV - 0.1 eV) energy interval. The problem of missing fuel pins was also investigated by Gavron and Smith[13] and it was shown that asymmetry in the fuel bundle can be used as an indication of a missing rod. In addition, they noted the possibility of developing time-spectra analysis methods. In this paper, we describe the recent progress in the time intervals matrix method for spent fuel assay which we presented earlier.[3]

LSDS Basics Methodology

LSDS represents a pure lead assembly usually driven by pulsed fast neutrons generated at or near the center of the installation (for example, the purity of LSDS-100 at the Institute for Nuclear Research of the Russian Academy of Sciences is 99.996 percent[16]). After the source pulse and while slowing-down, the neutrons undergo numerous elastic and inelastic scatterings. When their energies become less than necessary for inelastic scattering, about 0.5 MeV, all interactions are elastic. Neutrons slowed down through elastic scattering gather into a narrow energy group, which shifts towards smaller energies with increasing slowing-down time (Figure 1).

Correspondence between the time and the mean neutron energy[17] can be described as a function of time and the neutron's kinetic energy E:

$$E=K(t)/\ (t+t_0)^2 \qquad (1)$$

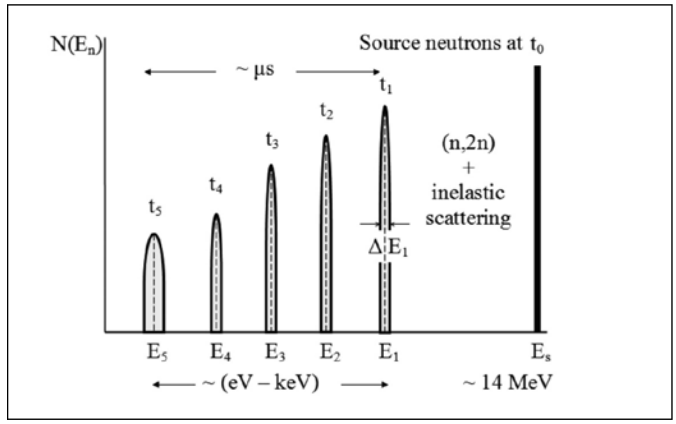
where the time t_0 (~0.3 μs[7]) can be considered as a correction for the fact that a neutron is not created with infinite energy but with energy E_0 ~14 MeV for a tritium target.[18] Function K(t) is usually considered as a slowing-down constant in the range of 160-183 keV·μs^2 for different LSDS that depends on the dimensions of the detector, source energy, and impurities in the lead. In their publication,[19] Alekseev et al. defined this function as:

$$K(t) = 165 - 15.2 \exp(-t/27.7)\ keV{\cdot}\mu s^2 \qquad (2)$$

(with uncertainty - 2 keV·μs^2). This dependency agrees with results of modeling that also show a decrease of $K(t)$ during the time (when $t<30\ \mu s$). [19]

One of the most important characteristics of LSDS, which should be also mentioned, is the energy resolution ($\Delta E/E$). For the ideal case, a value of resolution can be represented by the following expression:[20]

Figure 1. Schematic representation of evolution of neutron spectra in LSDS



$$\Delta E/E=[a_0^{\,2}+(kT/E)]^{1/2} \qquad (3)$$

where $a_0= 0.274;\ kT =0.0253\ eV$. But in the real case, the presence of the detectors and sources significantly perturbs the slowing characteristics; thus, the "ideal" value of energy resolution will become worse. In order to use all "bonuses" of LSDS, the influence of the detectors and sources to the distribution of interrogating neutrons should be eliminated.

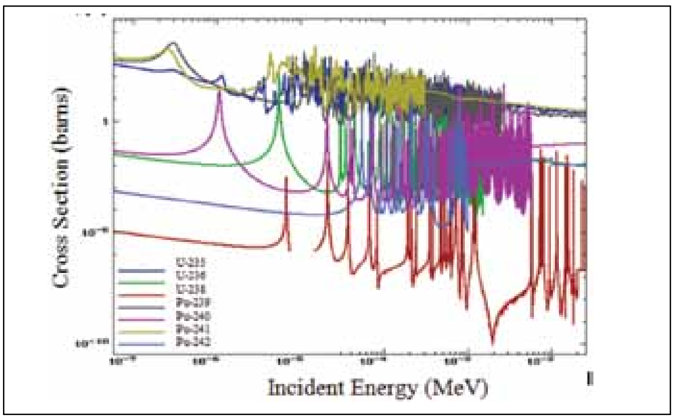
Simulation Method and Preliminary Results

Even so, the fact that neutrons are primarily monoenergetic with minor deviation from the peak value in each time moment after a fast neutron pulse can be utilized in the analysis of spent fuel (as has been shown in our previous modeling studies[3]). As follows from Figure 2, the fission cross sections of isotopes of U and Pu have significant differences in the different energy (time) intervals. Data is taken from the Evaluated Nuclear Data File (ENDF) managed by the Cross Section Evaluation Working Group of Brookhaven National Laboratory in the United States.

Previous modeling studies have utilized a relatively small set of fuel assemblies for the study and evaluation of LSDS methods. Thus, when fissile material (FM) is introduced into the LSDS, pulsed source neutrons during slowing-down in lead will induce fission reactions on various nuclides of FM. The structure of the isotopic responses will be directly correlated to neutron fission cross-sections as a function of energy. For example, in Figure 3, one can see that the peak near 640-960 μs in Pu-239 corresponds to the well-known resonance near 0.3 eV. Cross sectional data from various libraries were compiled to exhibit the simulated fission events after the neutron pulse. Thus, if time intervals for the measurements are correctly selected, then it will be possible to determine the FM concentration in a fuel assembly with good precision. In order to choose the matrix of time intervals, where large differences in the number of fissions of ^{235}U and ^{239}Pu are observed, the Los Alamos National Laboratory-developed Monte

Carlo neutron-particle code (MCNP4c[22]) was used to provide simulations of the number of fission events in a 1-kg FM sphere were performed. The relation of the number of fission events for ^{239}Pu to ^{235}U in various time moments after the neutron pulse indicated the appropriate time intervals.

Figure 2. Fission cross section of U and Pu isotopes in the energy region 0.1 eV – 50 keV (ENDF/B-VII.0)21



Time Intervals Matrix Analysis of ^{235}U, ^{239}Pu Content in FM

In our previous studies[3], the algorithm for determining ^{235}U and ^{239}Pu concentrations has been already developed in terms of fission rate matrix, which had been obtained for various nuclides. Thereto, in each time interval (i_{max}=6):

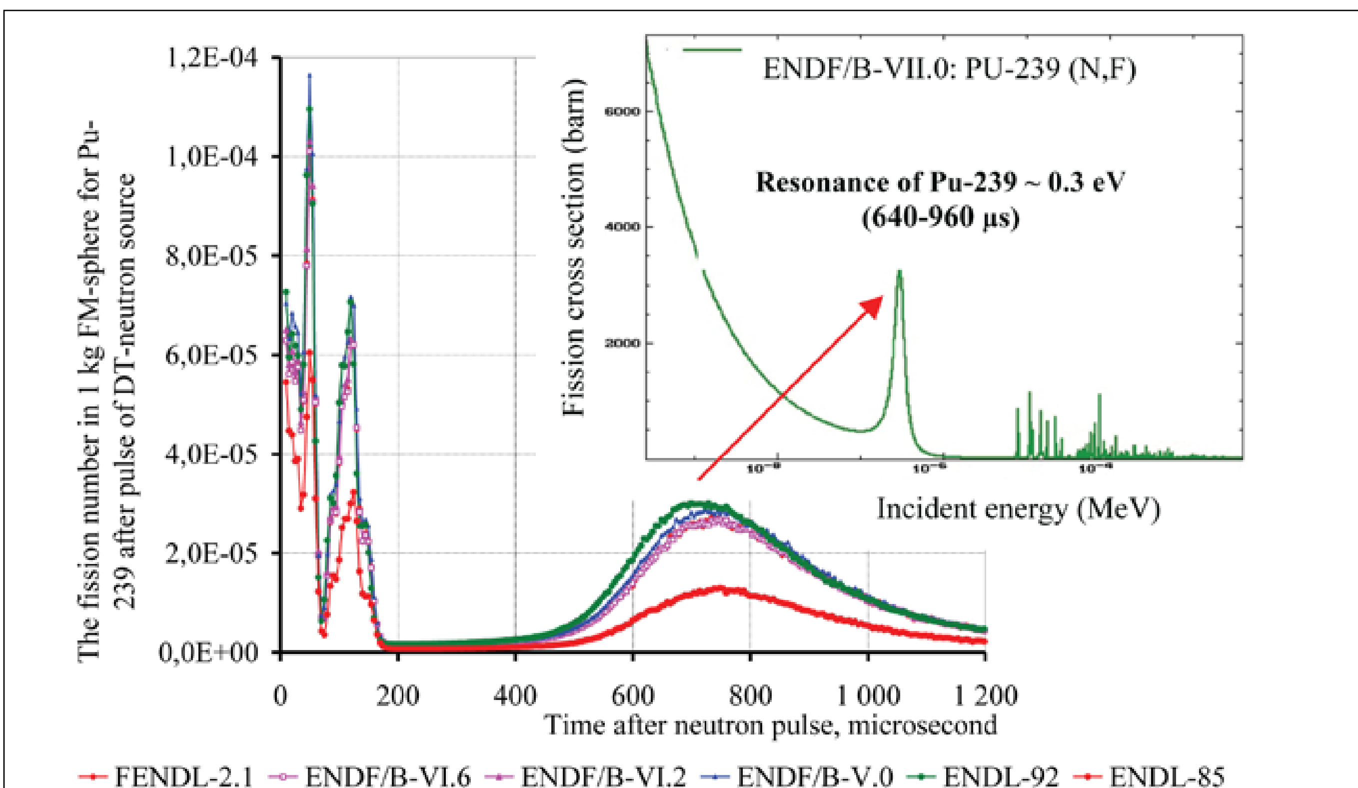
i=1 corresponds to the time interval 5-25 µs;
i=2 – (40-55) µs;
i=3 – (60-80) µs;
i=4 – (100-130) µs;
i=5 – (145-155) µs;
i=6 – (195-250) µs

normalized fission rates - $F_i(x_U;y_{Pu})$ have been determined (x_U – concentration of ^{235}U, y_{Pu} – concentration of ^{239}Pu). As an example, for case #1 when FM consists of 0.5 percent ^{239}Pu, 3 percent ^{235}U and ^{238}U six values have been defined

Thus, as a result of MCNP4c simulations performed for FM with various concentrations of ^{235}U and ^{239}Pu (sixteen cases have been taken for demonstration), six 4x4 matrices of $F_i(x_U;y_{Pu})$ have been obtained (Table 1). These matrices represented a so-called "calibrating system of samples" which thereafter was used to determine unknown concentrations.

In order to determine the unknown concentration of ^{235}U and ^{239}Pu, the minimum of the following function has been defined:

Figure 3. The fission number in 1 kg fissile material sphere (FM) for 239Pu after pulse of DT-neutron source3



$$J(x,y)=\sum_{i=1}^{n}\{\sum_{j=1}^{k}f_{ji}(x,y)-F_i\} \quad (4)$$

where F_i is the measured total fission rate in the sample for the *i-th* time interval (i = 1, ..., 6), $f_{ji}(x,y)$ – "deposit function" of *j-th* fissile nuclide to the total fission rate in *i-th* time interval.

Table 1. Example of normalized fission rates matrix $[F_i\ (xU;y_{Pu})]$ for *i-th* time interval

^{235}U ^{239}Pu	x_1 (3 percent)	x_2 (4 percent)	x_3 (5 percent)	x_4 (10 percent)
y_1 (0.5 percent)	$F_i\ (x_1,y_1)$	$F_i\ (x_2,y_1)$	$F_i\ (x_3,y_1)$	$F_i\ (x_4,y_1)$
y_2 (1 percent)	$F_i\ (x_1,y_2)$	$F_i\ (x_2,y_2)$	$F_i\ (x_3,y_2)$	$F_i\ (x_4,y_2)$
y_3 (1.5 percent)	$F_i\ (x_1,y_3)$	$F_i\ (x_2,y_3)$	$F_i\ (x_3,y_3)$	$F_i\ (x_4,y_3)$
y_4 (2 percent)	$F_i\ (x_1,y_4)$	$F_i\ (x_2,y_4)$	$F_i\ (x_3,y_4)$	$F_i\ (x_4,y_4)$

Due to the presence of local minima of function *J(x,y),* the absolute one was obtained using enumeration of possibilities in condensing grid: ranges of x, y segments were quantized with defined step (0,01 percent, as an example) and then the minimum of the function *J(x,y)* was defined; around this minimum a new region was constructed (with eight to ten steps, at least, for each variable) and the search for the minimum was continued with a step ten times lower than the previous one. In present research, this procedure was repeated several times, but in further works, it is planned that it be repeated until the solutions converge (with corresponding algorithmic procedure for verifying convergence).

For the *i-th* time, interval functions $f_j(x,y)$ were obtained by a piecewise-linear interpolation of the results presented in the final matrix:

$$f_j(x,y)=a+b(x-x_l)+c(y-y_k)+d(x-x_l)(y-y_k) \quad (5)$$

where x_l and y_k represent a pair of given concentrations when F_i was known.

In order to verify the proposed algorithm, several test problems with unknown isotopic composition were considered. As an example, let us consider a simple case when FM consists of ^{235}U (x=6 percent), ^{238}U and ^{239}Pu (y=1.3 percent).

For this case, the MCNP4c simulation was performed and six values - $F_i\ (x_U;y_{Pu})$ were obtained. These six values (each for a particular time interval) corresponded to the real measurement count rates and, in the present test, they acted as input parameters for the algorithm in question. Thus, by using the analytical algorithm, a pair of concentrations (x,y) were obtained as output parameters as given in Table 2.

Table 2. The comparison of concentrations obtained by means of analytical algorithm using various time intervals to the real concentration used in MCNP simulations

Case number	#1	
Isotopes of interest	^{235}U	^{239}Pu
Real concentrations	6 percent	1,3 percent
Concentrations obtained using analytical algorithm		
Using all six time intervals: *i=1,2,3,4,5,6*	5,77 percent	1,46 percent
Using time intervals: *i=2,3,4,5*	5,72 percent	1,49 percent
Using time intervals: *i=3,4,5*	5,94 percent	1,49 percent
Using time intervals: *i=3,4*	5,96 percent	1,52 percent

From Table 2, one can see that the analytical algorithm allows one to get concentrations of various isotopes of interest with good precision (the differences between calculated results and real values do not exceed a few percent and can be decreased by increasing the matrix rank). However, this difference strongly depends on the time intervals that were used in the algorithm for various isotopes. Thus, it is still necessary to perform an optimization of the algorithm in order to get high precision results (particularly, sets of used time intervals should be chosen for each isotope).

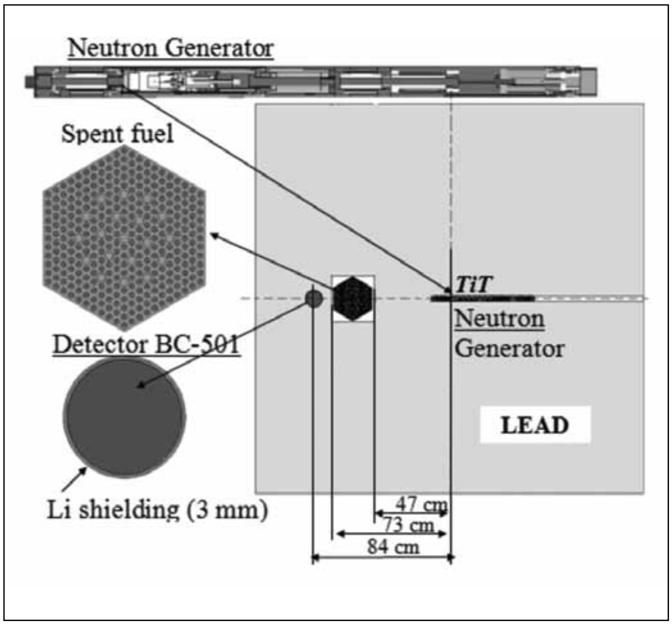
Real Configuration

As mentioned above, in the real measurement case, a presence of the detectors and sources will significantly perturb the ideal slowing characteristics of LSDS and as a result, time intervals matrix will be changed. Therefore, as opposed to "homogeneous-volume approximations" used in our previous research,[3] in this work we describe the detailed Monte Carlo models of real fuel assemblies, as well as the effects of the influence of the scintillation detector to the system in question. Monte Carlo (MCNP) simulations[22] were carried out to estimate reaction rates and scintillation detector response from spent fuel composition (VVER-1000 type) in LSDS. Concentration of fissile isotopes in the fuel assembly varied during the calculations corresponding to the range of experimental results.[23]

The energies of the source particles were sampled for three cases:

- for the point DT pulsed neutron source with mean energy 14.3 MeV;
- for the real target of pulsed neutron generator (ING-10-20-120 – a vacuum tube-based pulsed neutron generator for logging equipment[24]) taking into account anisotropic angular distribution of neutrons;
- for the real pulsed neutron generator (ING-10-20-120 type) with considering most of factors affecting neutron and secondary photon output.[24]

Figure 4. Model of the simulated configurations



The neutron source was placed in the center of a 240 cm lead cube at a distance of 47 cm from the fuel assembly. A detector of type BC-501[25] with a density of 0.901 g/cm^3 was located 84 cm from source (Figure 4).

In the Monte Carlo calculations, a few cases were modeled in order to investigate and eliminate the influence of the detector, the neutron generator, etc. to the distribution of interrogating neutrons and detector response:

- LSDS with the point DT pulsed neutron source, spent fuel assembly, and detector without Li screen (case 1);
- LSDS with the point DT pulsed neutron source, spent fuel assembly, and detector with Li covering (case 2);
- LSDS with the point DT pulsed neutron source, spent fuel assembly, detector with Li covering and measurement chamber covered with Li shielding (case 3);
- LSDS with source as the real target of pulse neutron generator (ING-10-20-120 type), spent fuel assembly and detector with Li covering (case 4);
- LSDS with source as the real pulse neutron generator (ING-10-20-120 type), spent fuel assembly and detector with Li covering (case 5).

Figure 5. Time distributions of response of neutrons in the scintillation detectors for two cases (1 and 2)

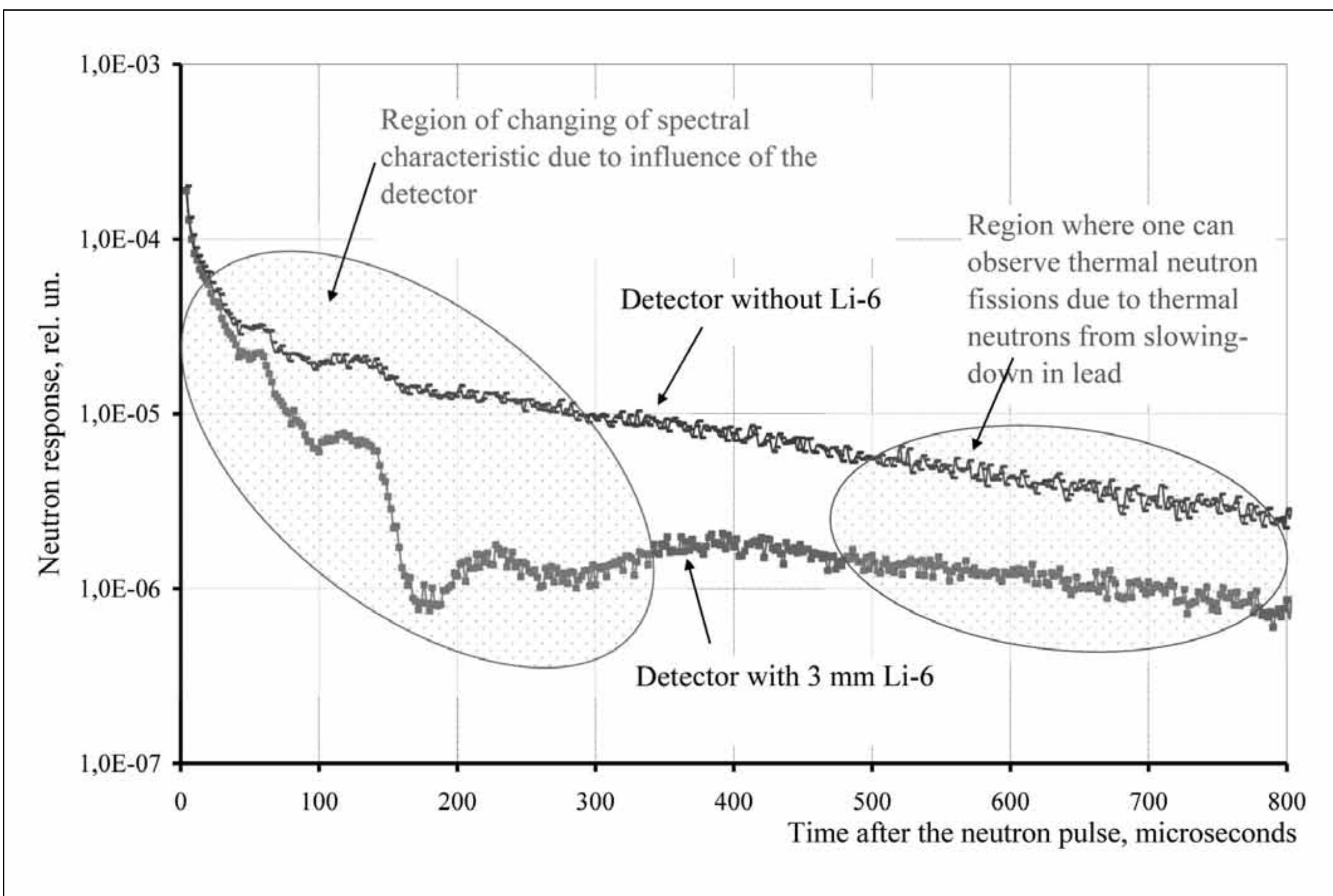
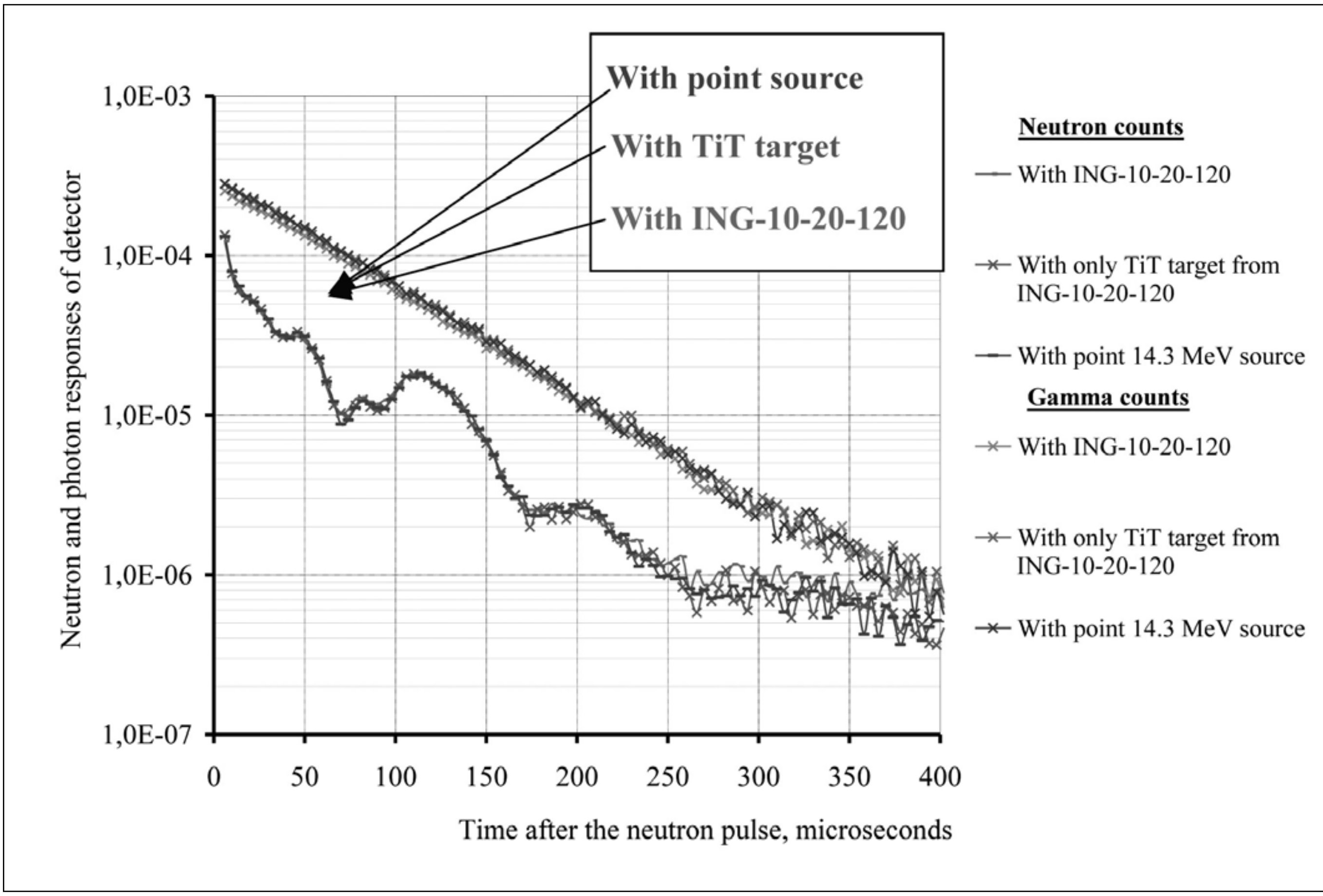


Figure 6. Time distributions of response of n and γ in the scintillation detectors for three cases (3, 4, 5)



MCNP simulations were performed using the ENDF/B-VI data library. Inaccuracies related to using different data libraries for the lead moderator were considered in an earlier paper.[26] For example, using data from two different libraries, the difference between time and energy distributions of neutrons were 50 percent for the lead moderator. Therefore, in our previous research[3] for justifying the technique of Pu evaluation based on the chosen matrix of time intervals, all simulations were done using various data libraries (as shown in Figure 3).

Influence of the Scintillation Detector to the Spent Fuel Response

The presence of the scintillation detector in the LSDS significantly perturbs the slowing down characteristics and can lead to tails in the distribution of interrogating neutrons. To eliminate this effect, a detector was covered by a 3-mm lithium screen. In Figure 5, one can see the influence of the detector and the lithium covering on the neutron response. By using a Li cover, thermal neutrons from the hydrogen-containing material did not enter the LSDS. The thickness and the shielding material of the detector (lithium instead of cadmium etc.) were chosen based on our previous studies and development of a composite scintillator.[27]

Despite the fact that covering detectors with lithium allowed a significant decrease to low-energy tails in distribution of interrogating neutrons, it is still interesting to investigate the applicability of the composite scintillator, which was developed for decreasing the load on the scintillation channels in fissile material detection and control installations with pulsed neutron sources.[27]

Influence of the Neutron Generator on the Spent Fuel Response

Among the sources that can be used in LSDS, one usually gives preference to accelerators instead of portable neutron generators (NG). Due to advances in the design of compact NGs during the last few years, modern instruments are capable of operating at sustained neutron output rates of more than 10^{10} - 10^{11} neutrons per second. This fact has led to renewed interest in their use for a variety of commercial applications. However, during the selection of a portable neutron generator one should be careful because, for example, the 14.1 MeV neutrons produced in a deuterium + tritium fusion reaction can also be accompanied by a high photon and thermal neutron background for the particular NG. [28]

In the present application, various types of compact neutron generators can influence the slowing characteristics of LSDS in different ways that can lead to tails in the distribution of interrogating neutrons. Based on our previous research[28], ING-10-20-120 has been chosen and examined for possible influence to the spent fuel response. The Monte Carlo simulations were performed for three cases (3, 4, and 5) to investigate changes in neutron and photon distributions owing to the effect of the NG. In Figure 6, one can see that the neutron generator of ING-10-20-120 type does not influence the detector response and can be considered as a point pulsed neutron source with energy 14.3 MeV.

Matrix of Time Intervals for Analysis of ^{235}U and ^{239}Pu Content in a Real Spent Fuel Assembly

Previously,[3] we chose a matrix of time intervals where a large difference in the fission number of ^{235}U and ^{239}Pu was observed for homogeneous-volume approximations. Realization of the theoretical design to practical implementation is always an intricate problem because it is supposed to investigate the real spent fuel assembly. Therefore, fission rates have been simulated for different nuclides in the real spent fuel assembly. As in the model simulations, time intervals have been selected where the big differences in fission number of ^{235}U, ^{239}Pu and ^{241}Pu are observed: (5-40) µs, (40-60) µs, (60-97) µs, (97-133) µs, (133-164) µs, (164-260) µs, (260-400) µs. These intervals do not vary much from those selected in previous work, but they allow the estimate of the content of ^{241}Pu and take into account the heterogeneous structure of nuclear material.

Influence of Self-shielding Effect and Self-multiplication Factor to the Spent Fuel Response

While conversion from small nuclear material sample to the real fuel assembly, a few uncertainty effects, such as neutron self-multiplication factor and neutron self-shielding effect, can significantly increase. The first one will mostly depend on the neutron energy spectrum, sample composition, sample density, sample geometry, and neutron reflection. With increasing the plutonium masses, the neutron self-multiplication factor will go up. As for the thermal neutron self-shielding, which is also dependent on sample geometry, enrichment, density, chemical composition, and neutron energy spectrum, one should take into account when the energy of neutrons is low or if significant amount of moderator is present in the interrogated sample. Whereas neutron energy is quite low in LSDS and in the spent fuel there is a significant amount of plutonium, both neutron self-multiplication factor and neutron self-shielding effect have to be taken into consideration during simulations. Corresponding to the type of non-destructive installation, these two effects can be considered as competitive because the first one leads to increase of number of fissions in relation to the mass of ^{239}Pu" while the other one can lead to decrease of number of fissions in relation to the mass of ^{239}Pu". MCNP simulations performed for a spent fuel assembly with isotopic composition corresponding to 70 MWd/MTU for VVER-fuel with original concentration of ^{235}U - 3.6 percent[29] show that the number of fissions induced by interrogating neutrons (0.46 eV – 100 keV energy range) in the outer tier of fuel rods is 1.3 times higher than in the inner layer (Figure 7). But for total number of fissions (including induced by neutrons with energy higher than 0.7 MeV), this value goes down to 1.2.

Influence of Various Nuclides in Spent Fuel to the Total Number of Fission Neutrons and Analysis of ^{235}U, ^{239}Pu and ^{241}Pu Content in a Real Spent Fuel Assembly

For the practical realization of the proposed method one also should take into account that in addition to ^{239}Pu, ^{241}Pu, ^{235}U, and ^{238}U, there are other fissile nuclides (such as, ^{234}U, ^{236}U, ^{237}Np, ^{238}Pu, ^{240}Pu, and ^{242}Pu) in spent fuel which can influence the detector's response. To estimate the possible effect of these nuclides to the total output of neutrons, MCNP calculations were performed for the same 70 MWd/MTU VVER-fuel[29] and numbers of neutrons per fission for all nuclides were included in calculations.

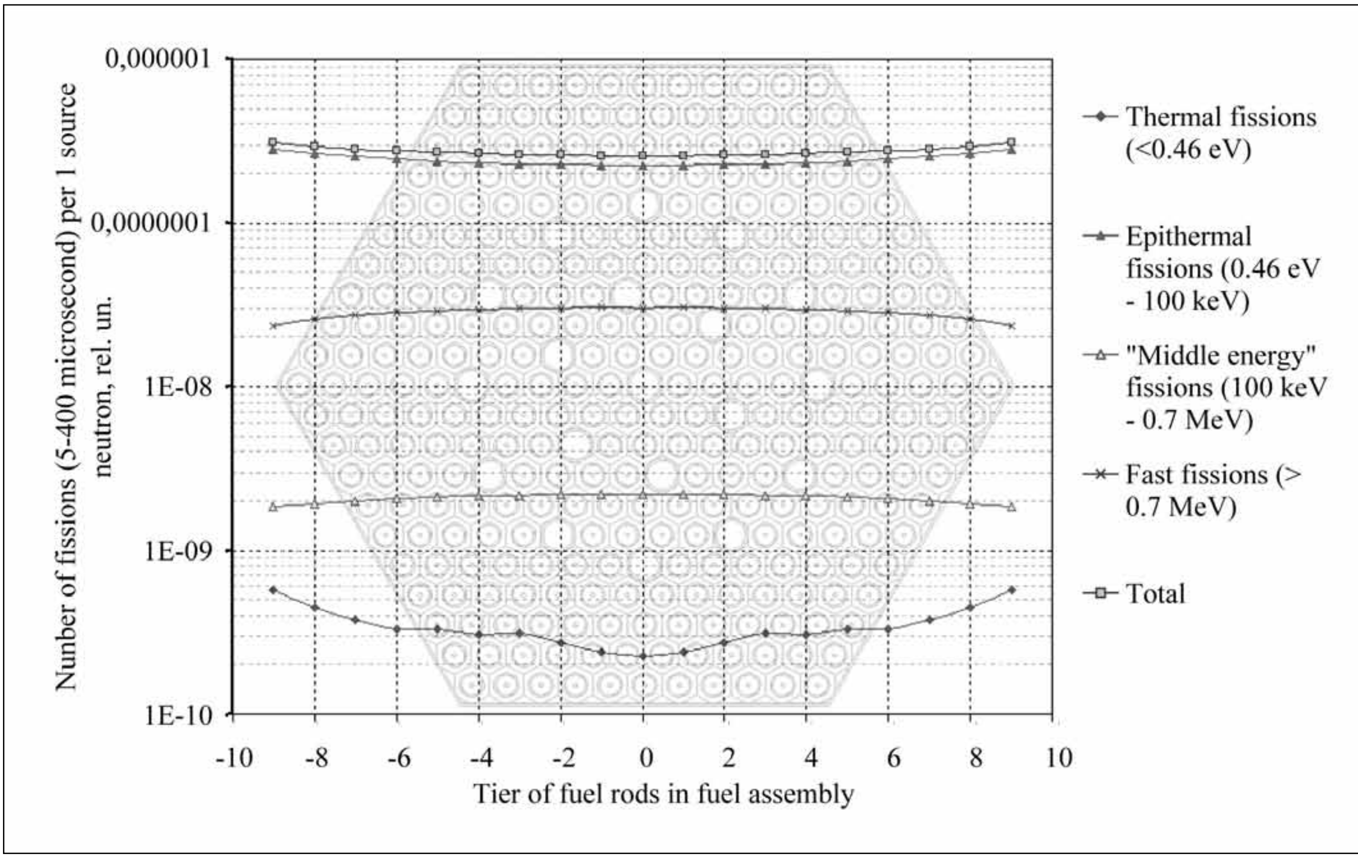
Figure 8 shows that nuclides, such as ^{234}U, ^{237}Np, ^{242}Pu, almost have no influence on total amount of neutrons and only 1-2 percent of fission neutrons are related to ^{236}U, ^{238}Pu, and ^{240}Pu. Moreover, one can see that in the time interval from 164 to 260 µs more than 60& of neutrons are originated by ^{241}Pu, whereas, in the time interval from 40 to 60 µs, about 60 percent of neutrons are originated by ^{239}Pu. These values can be utilized in order to optimize the analytical algorithm described above. For example, in the first round, the time interval from 164 to 260 µs can be used to obtain a concentration of ^{241}Pu and, the time interval from 40 to 60 µs - to obtain a concentration of ^{239}Pu.

Of course, in practice we should solve the more complex task of determining the minimum function of measured response of the detector, which is proportional to the total number of fission neutrons, thus, the main algorithm will not be changed much. The possibility of using a 2 – 5-µs interval mode for direct measurements of Pu and U isotopes should be also taken into account for future applications of LSDS.

Conclusions

The study of the potential of using LSDS for high accuracy ^{235}U and ^{239}Pu assay in spent fuel assemblies has been described in this

Figure 7. Number of fissions in volume unit (5-400 microseconds) in spent fuel assembly



paper. It has been shown that it is also possible to measure the amount of the ^{241}Pu in the selected time intervals. However, it is still necessary to optimize the analytical algorithm in order to get high precision results, particularly sets of used time intervals should be chosen for each isotope. Preliminary studies of the influence of the neutron generator on the detector response showed that it is minimal to the slowing characteristics. Thus, the value of energy resolution will not be significantly changed and, within the bounds of LSDS application, this NG can be considered as a point pulse neutron source with energy 14.3 MeV. At the same time, it was shown that usage of ordinary scintillation detection for measurements of spent fuel response in LSDS will destroy the time interval matrix and, thus, the ability to determine concentrations of ^{235}U, ^{239}Pu, and ^{241}Pu with good precision. This problem was solved by using Li shielding on the detector which significantly decreases the influence of the scintillation detector to the distribution of interrogating neutrons. However, it is still interesting to investigate the applicability of the composite scintillation detector for these purposes.[27] MCNP simulations performed for spent fuel assembly with isotopic composition corresponding to 70 MWd/MTU for VVER-fuel with original concentration of ^{235}U - 3.6 percent showed that the number of fissions induced by interrogating neutrons (0.46 eV – 100 keV energy range) in the outer tier of fuel rods is 1.3 times higher than in the inner layer (but, for total number of fissions, this value goes down to 1.2). Therefore, when converting from small nuclear material sample to the real fuel assembly, both effects (neutron self-multiplication factor and neutron self-shielding effect) should be taken into account in order to use a method of direct measurement of ^{235}U and ^{239}Pu concentrations.

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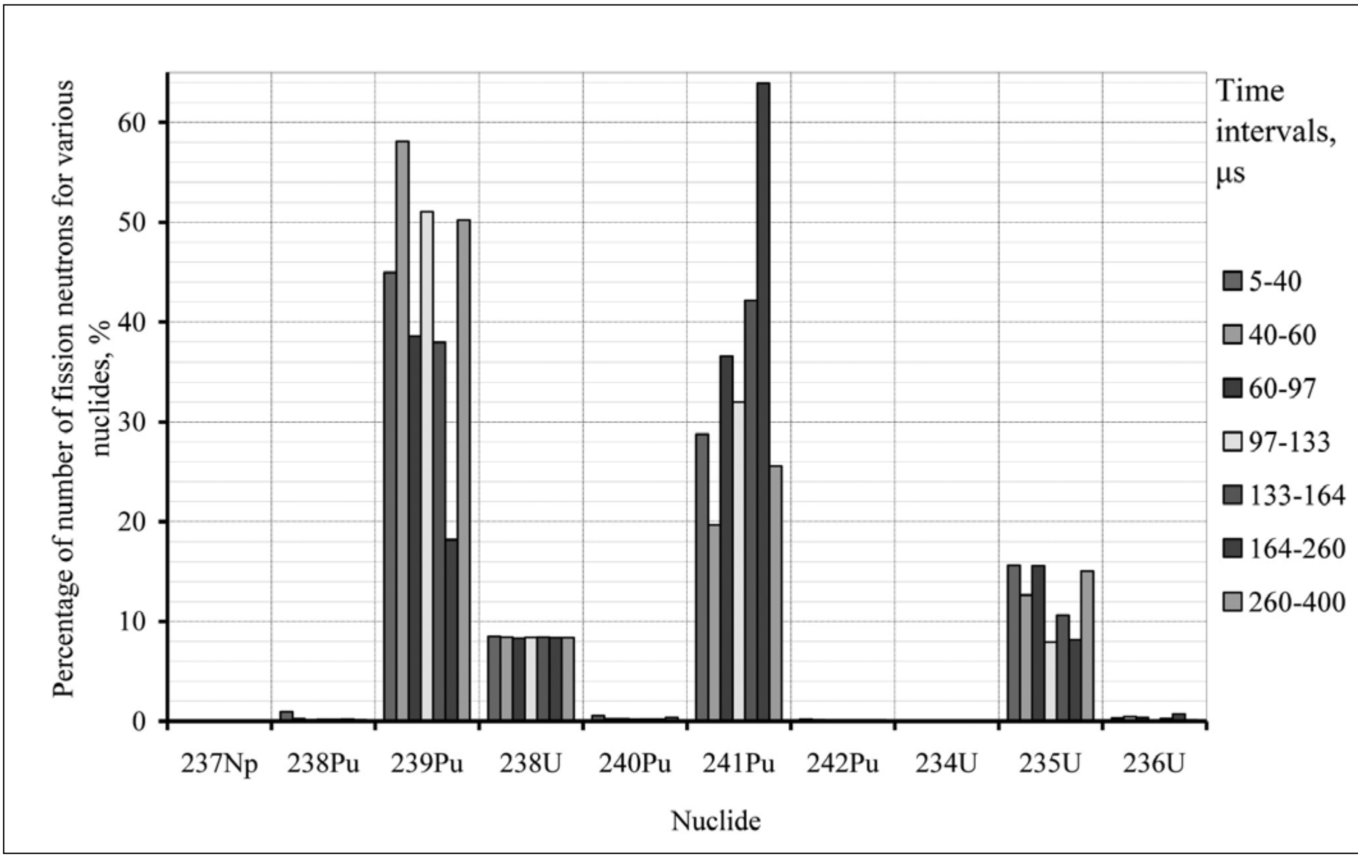
Figure 8. Percentage of number of fission neutrons for various nuclides in spent fuel assembly in different time intervals



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Use of a Microsphere Fingerprint for Identity Verification of Fuel Pebbles in a Pebble-fueled HTGR

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Abstract
The continued development of a commercial-scale pebble-fueled high-temperature gas-cooled reactor (PF-HTGR) in the People's Republic of China (PRC) will lead to an exportable design within the next fifteen years. The potential export of the design has renewed the need for a safeguards system capable of adequately accounting for the fuel present at a PF-HTGR facility. Previously proposed methods utilize extensive redundant containment and surveillance (C/S) systems or some combination of item- and bulk-type material accountancy that are incapable of restoring continuity of knowledge in the event of a failure of the C/S or accountancy systems. Using a recently proposed verification system based on the use of a microsphere fingerprint in each fuel pebble, the uncertainties in the material unaccounted for (MUF) in potential material accountancy systems were explored for an abrupt and protracted diversion from a hybrid safeguards approach and a new item-type safeguards approach.

Introduction
The pebble-fueled high-temperature gas-cooled reactor (PF-HTGR) design was developed by the Federal Republic of Germany in the 1960s with the design and construction of the Arbeitsgemeinschaft Versuchsreaktor (AVR).[1] Germany continued development of the design with construction of the Thorium High-temperature Reactor (THTR) in 1967.[2] From these beginnings, the PF-HTGR has seen development in more recent years in the Republic of South Africa (RSA) and the PRC. RSA began development of the Pebble Bed Modular Reactor (PBMR) in 1993, but its continued pursuit was abandoned in late 2010 when the largest investor in the program, RSA, withdrew.[3] The PRC began its PF-HTGR program in 1992 with the development of the HTR-10, a 10 MW_t research facility located at the Institute of Nuclear Energy Technology site near Tsinghua University in Beijing. Using knowledge gained from the HTR-10, the PRC began development of the High-temperature Reactor-Pebble Bed Module (HTR-PM), a prototype PF-HTGR facility, in 2001. Set to begin operation by 2015, the PRC has plans to construct an additional eighteen modules at the Shidaowan site in Weihai City.[4] With the expected success of the PRC PF-HTGR program, it can be reasonably expected that the design will be exported beyond Chinese borders. Until recently, as a nuclear weapon state (NWS), safeguards for the Chinese PF-HTGR reactors have not been considered a priority by the international safeguards community. However, once the design is exported to a non-nuclear weapon state (NNWS) the availability of a safeguards system that can adequately account for the nuclear material present is a necessity.

Ultrasound-based Microsphere Fingerprint Verification System

To verify the identity of the fuel pebbles circulating throughout the reactor facility, a safeguards system using ultrasound to image a microsphere fingerprint has been proposed.[5,6] This microsphere fingerprint is composed of at least three ZrO_2-Y_2O_3 microspheres that have been randomly dispersed in the fueled region of each fuel pebble. Simulating the random repetition associated with the use of three microspheres and an ultrasound imaging system with a realistic resolution of 500 μm, the system is expected to mismatch approximately 0.006 percent of pebbles over the lifetime of the reactor.[5]

Description of Facility
The reference facility considered for the determination of material unaccounted for (MUF) uncertainties resembles the cogeneration facility redesign of the PBMR with two reactor units each capable of producing 250 $MW_{(th)}$ with a combined output of 200 $MW_{(e)}$.[7]

The material flow for the reference PF-HTGR facility can be seen in Figure 1. For each unit, containers holding 1,000 fuel pebbles with 9 g of 8.0 wt percent ^{235}U are brought into the facility and placed in a storage area. There is a six-month supply of fresh fuel maintained in the storage areas at all times. When required, a container is loaded into a fuel loading machine. Each day, 350 pebbles are released into the fuel handling system, which individually places each pebble in the reactor core. When operating at equilibrium, 360,000 pebbles are in the reactor core. The fuel handling system removes pebbles at the bottom of the reactor core. Any damaged pebbles are separated into a waste container. A burnup analysis is performed on undamaged pebbles. The undamaged pebbles are separated and either returned to the reactor

Figure 1. The material flow for the reference PF-HTGR facility evaluated

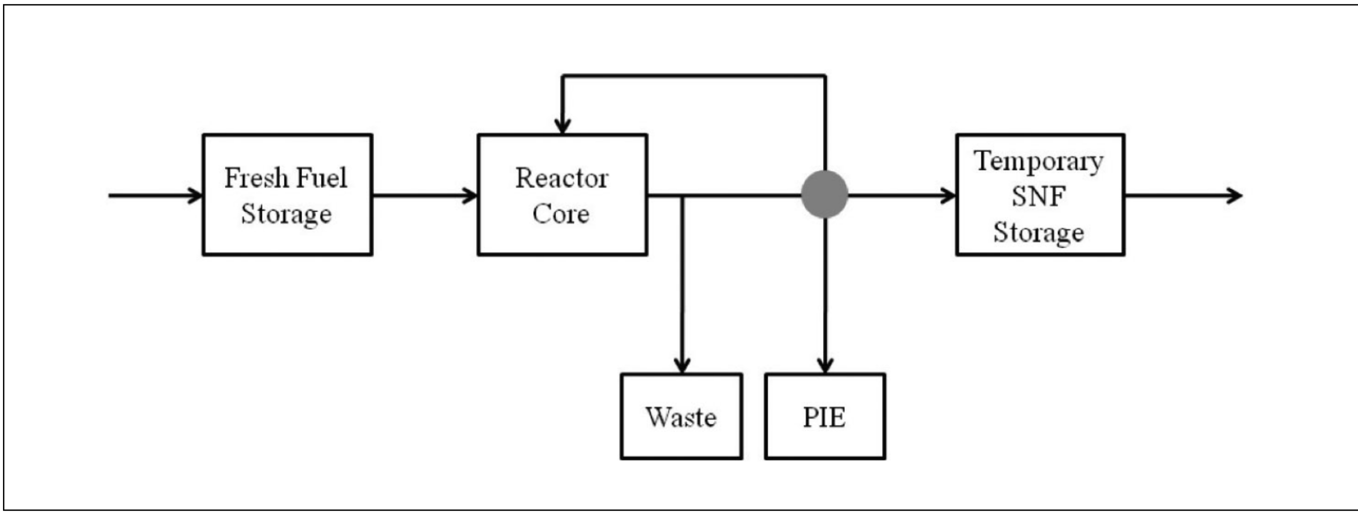
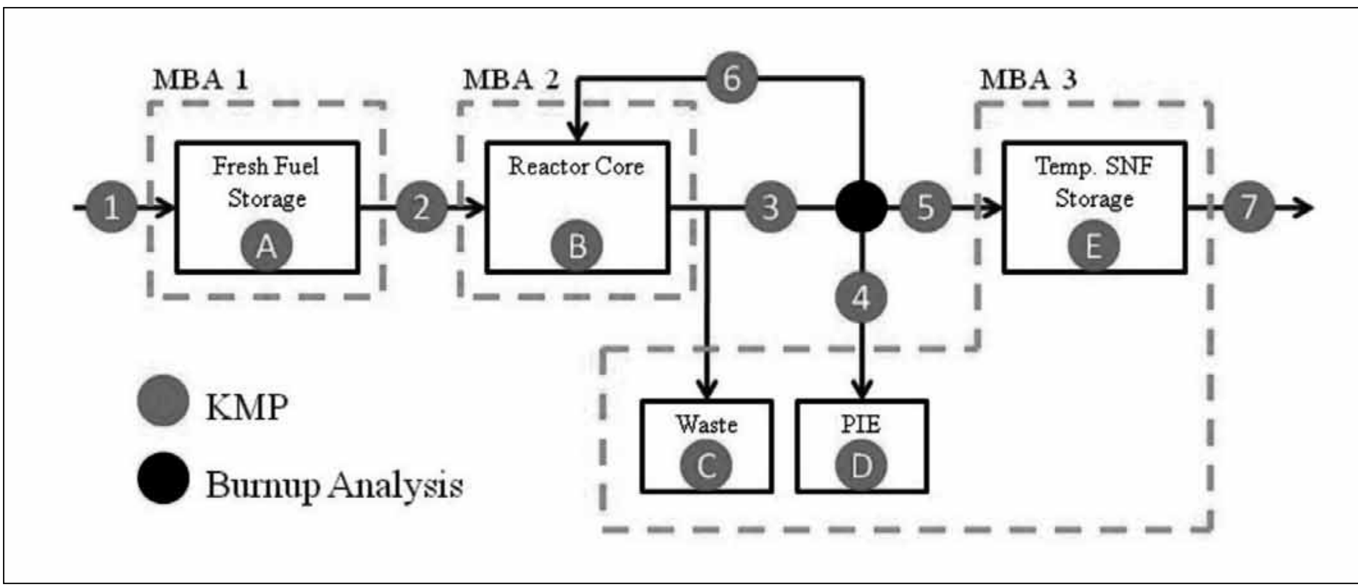


Figure 2. The previously proposed hybrid safeguards approach for a PF-HTGR[8,9]



core, classified as spent fuel, or extracted for a post irradiation examination (PIE). Each day approximately 3,000 pebbles are circulated back to the reactor core and an additional 350 pebbles are classified as spent fuel. Pebbles classified as spent fuel are stored in a temporary storage area that holds a three-month inventory of spent fuel. The spent fuel pebbles are held in containers capable of holding 2,000 pebbles each. Each spent fuel pebble contains approximately 0.114 g of plutonium when discharged.

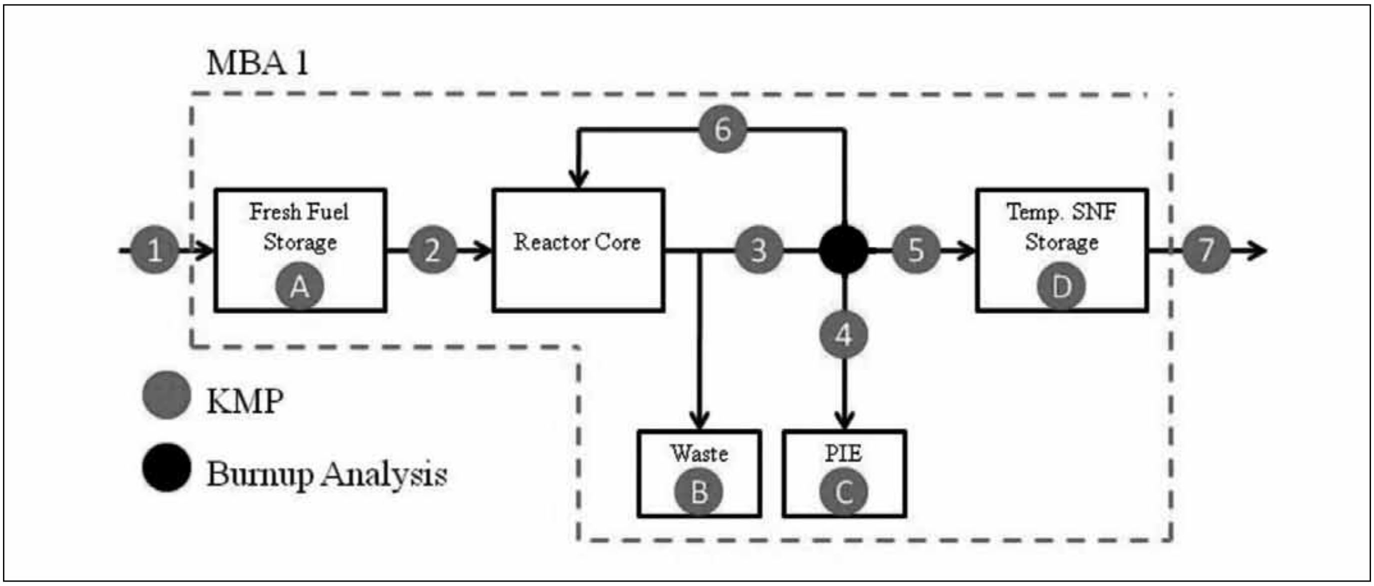
Hybrid Safeguards Approach

The proposed hybrid safeguards approach, as seen in Figure 2, utilizes three separate material balance areas (MBAs) – two item-type material MBAs and a single bulk-type material MBA.

MBA 1 and MBA 3 utilize item-type material accountancy measures, while MBA 2 utilizes bulk-type material accountancy measures. The material accountancy measures performed at each key measurement point (KMP) are:[8,9]

- KMP 1 and A: Each container is counted, verified by its serial number, and weighed. ^{235}U content is verified randomly by NDA.
- KMP 2, 3, 4, 5, and 6: Pebbles are counted as they pass through the fuel handling system.
- KMP B: Using pebble counters located at KMP 2 and 3 and a power level monitor, the nuclear material content of the core is estimated using burnup codes.

Figure 3. The proposed item-type material approach utilizing microsphere fingerprint verification system



- KMP C and D: Storage/broken pebble waste containers are counted, verified, and weighed. Plutonium content can be verified using neutron coincidence.
- KMP E: Each container is filled, counted, verified by its serial number and weighed. Plutonium content can be verified using a neutron coincidence system similar to the Waste Drum Assay System.
- KMP 7: Each container is counted, verified by its serial number, and weighed. Plutonium content can be verified using neutron coincidence.

Additional containment and surveillance (C/S) measures employed at each KMP can be found in References 8 and 9. Since no direct item accountancy can be performed on pebbles that reside in the reactor core, dual C/S measures are applied.

Item-type Safeguards Approach

The proposed item-type safeguards approach for the PF-HTGR is depicted in Figure 3. The approach utilizes a single MBA. The accountancy measures utilized at each KMP within the MBA are:

- KMP 1 and A: Each container is counted, verified by its serial number and its integrity confirmed.
- KMP 2, 3, 4, 5, and 6: Each pebble is counted and verified using microsphere fingerprint.
- KMP B and C: Storage/broken pebble waste containers are counted and verified. This material is expected to be in a loose form and will most likely also be weighed and plutonium content will be verified.
- KMP D: Each container is filled, counted, verified by its serial number and its integrity confirmed.

Like the hybrid safeguards approach, direct item accountancy and verification of fuel currently in the core is not possible. As such, dual C/S measures are applied to the reactor core.

Determination of MUF Uncertainties

Each of the safeguards approaches were analyzed to determine the uncertainty in the amount of material unaccounted for (σ_{MUF}) generated in each MBA. For each MBA, the non-detection probability (β) for an abrupt and protracted diversion of 1 significant quantity (SQ) of fresh fuel and spent fuel was found. Expected MUF was calculated using the following equation:[10]

$$MUF = (PB + X - Y) - PE \tag{1}$$

where, PB is the beginning physical inventory, X are increases in inventory, Y are decreases in inventory, and PE is the ending physical inventory for a given material balance period (MBP).

The MUF and σ_{MUF} equations for each MBA in the hybrid approach are:

MBA 1:

$$MUF = (KMP\ A + KMP\ 1 - KMP\ 2) - KMP\ A \tag{2}$$

$$\sigma_{MUF} = \sqrt{2\sigma^2_{KMP\ A} + \sigma^2_{KMP\ 1} + \sigma^2_{KMP\ 2}} \tag{3}$$

MBA 3:

$$\begin{aligned} MUF = [(&KMP\ C + KMP\ D + KMP\ E) + \\ &(KMP\ 4 + KMP\ 5) - KMP\ 7)] \\ &- (KMP\ C + KMP\ D + KMP\ E) \end{aligned} \tag{4}$$

$$\sigma_{MUF} = \sqrt{\begin{matrix}2\sigma^2_{KMP\ C} + 2\sigma^2_{KMP\ D} + 2\sigma^2_{KMP\ E} + \\ \sigma^2_{KMP\ 4} + \sigma^2_{KMP\ 5} + \sigma^2_{KMP\ 7}\end{matrix}} \quad (5)$$

There is no MUF equation for MBA 2 because direct item accountancy cannot be performed on pebbles that are currently in the core.

The MUF and σ_{MUF} equations for the single MBA in the item approach is:

$$\begin{aligned} MUF = [(&KMP\ A + KMP\ B + KMP\ C + \\ &KMP\ D) + KMP\ 1 - KMP\ 7] \\ &- (KMP\ A + KMP\ B + KMP\ C + KMP\ D) \end{aligned} \quad (6)$$

$$\sigma_{MUF} = \sqrt{\begin{matrix}2\sigma^2_{KMP\ A} + 2\sigma^2_{KMP\ B} + 2\sigma^2_{KMP\ C} + \\ 2\sigma^2_{KMP\ D} + \sigma^2_{KMP\ 1} + \sigma^2_{KMP\ 7}\end{matrix}} \quad (7)$$

In the analysis of each approach, it was assumed that the broken pebble waste container remained at the facility for the lifetime of the reactor based on the operational expectations of the THTR.[11] The PIE was assumed to occur on-site in a specified area where the waste would also be stored. For these calculations the number of pebbles going into the waste and PIE areas was neglected since the number of damaged pebbles and pebbles removed for PIE are based on operational characteristics of each reactor.

For each approach, the number of pebbles that are at, or passes through, each KMP and their respective uncertainties can be found in Table 1.

Using Equations 2, 4, and 6, MUF for each MBA in both approaches was found to be zero. In the hybrid approach, there was a 1 percent uncertainty in item counting and a 5 percent uncertainty in weighing of containers. For MBA 1 and MBA 3 in the hybrid approach, σ_{MUF} was calculated to be 2,306 and 1,279 pebbles, respectively. For the item approach, a 1 percent uncertainty in item counting of containers and pebbles in each container was included. The calculated σ_{MUF} was 315 pebbles.

Non-Detection Probability (β) Determination

To determine β, the non-detection probability, for an abrupt and protracted diversion in each MBA, the NORMINV and NORMDIST functions in Excel were used. The false alarm rate was set at 5 percent. For the diversion scenarios, 1 SQ of fresh fuel and spent fuel was equal to 104,167 pebbles and 70,175 pebbles, respectively. In the protracted diversion, 1,000 pebbles were diverted during each MBP. In the hybrid approach, MBA 1 has a twelve-month MBP and MBA 3 has a three-month MBP. The single MBA in the item approach has a three-month MBP.

Table 1. Number of pebbles at, or that pass through, each KMP and their expected uncertainties PF-HTGR[8,9]

		Quantity of Pebbles	Uncertainty (in Pebbles)
Hybrid Approach			
MBA 1	KMP 1	126000	1568
	KMP A	63000	797
	KMP 2	126000	1260
MBA 3	KMP 4	0	0
	KMP 5	31500	315
	KMP C	0	0
	KMP D	0	0
	KMP E	63000	821
	KMP 7	31500	434
Item-type Approach			
MBA 1	KMP 1	31500	223
	KMP A	6300	0.049
	KMP B	0	0
	KMP C	0	0
	KMP D	31500	0.025
	KMP 7	31500	223

For a single reactor unit, the calculated β for the abrupt diversion of 1 SQ of either fresh fuel or spent fuel was zero for all three evaluated MBAs. This means that the hybrid approach and the item-type approach are both capable of detecting the diversion of 1 SQ worth of fresh or spent fuel. This is expected because a successful abrupt diversion of 1 SQ worth of fresh fuel pebbles would be equivalent to the removal of 30 percent of the core contents. For spent fuel, it would be equivalent to abruptly diverting 20 percent of the core contents. The abrupt diversion 1 SQ of pebbles from the fuel storage areas would also prove to be difficult, if not impossible. The supply and inventory limits placed on the amount of fuel that can be present at any one time in these areas insures there will never be 1 SQ worth of material in either area at a single time.

In the case of a protracted diversion, 1,000 fuel pebbles were diverted during each MBP from a single MBA. To successfully divert 1 SQ, the adversary would have to repeat the diversion undetected some 104 times for fresh fuel and seventy times for spent fuel pebbles. The resulting β for this diversion scenario can be found in Table 2.

The results show that even for a protracted diversion of at least one container worth of fresh fuel pebbles, or a half-container worth of spent fuel pebbles, each approach can be expected to successfully detect the diversion before 1 SQ of material has been diverted.

Figure 4. Plot showing that as additional PF-HTGR units are built in a country the non-detection probability for the protracted diversion of 1 SQ increases

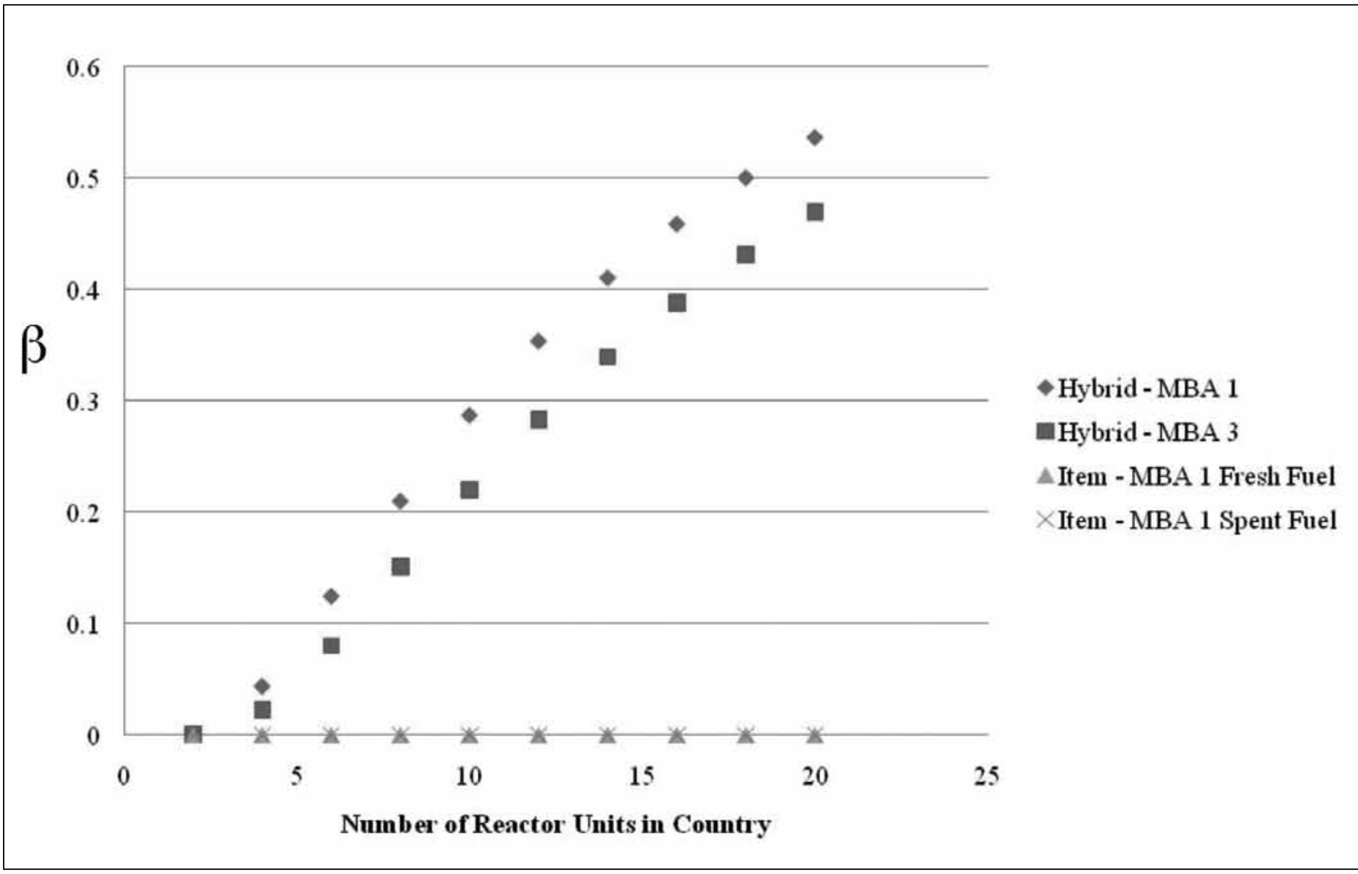


Table 2. The calculated β for a protracted diversion

	β
Hybrid Approach	
MBA 1	3.8 E -6
MBA 3	2.7 E -7
Item-type Approach	
MBA 1 - Fresh Fuel	< 1 E -9
MBA 2 - Spent Fuel	< 1 E -9

These results however, only account for one of the two units expected at a commercial PF-HTGR facility. As additional units are built within a country, the adversary can spread those 1,000 pebble diversions over several facilities. The resulting increase in β was calculated and plotted for each MBA in each approach in Figure 4.

The plot in Figure 4 shows that the hybrid safeguards approach, while potentially successful at detecting the abrupt or protracted diversion of 1 SQ of material from a single reactor unit, cannot adequately detect the protracted diversion of 1 SQ of material spread across multiple facilities. However, a PF-HTGR safeguards approach that is built upon the microsphere fingerprint verification system retains its robustness and reliability in this same scenario. In fact, in order to reach a 5 percent non-detection probability in the protracted diversion of 1 SQ worth of fresh fuel pebbles, a country would need to have 96 PF-HTGR reactor units, or forty-eight separate reactor facilities that pebbles were being diverted from. For the protracted diversion of 1 SQ worth of spent fuel pebbles, a country would need to divert pebbles from sixty-four units, or thirty-two different PF-HTGR facilities.

Conclusions

As the PF-HTGR is further developed and deployed across the world, a robust and effective safeguards system will be needed. The proposed dual C/S dependent and hybrid safeguards approaches are not capable of verifying the identity of each fuel pebble. This presents two challenges to the approaches: the inability to restore CoK in all scenarios and the introduction of some amount of MUF to the facility. If the PF-HTGR is to be deployed worldwide, the safeguards system must have the ability to perform identity verification to overcome these challenges. The microsphere fingerprint verification system proposed in this work was evaluated and shown to fulfill this need for unique identification. By using ultrasound to image a random configuration of inert microspheres within the pebble, a unique fingerprint was created for each pebble. It was shown that the expected number of mismatched fingerprints is low over the reactor lifetime. This property can be reduced if the resolution of the imaging system is improved or if more than three microspheres are used to create the fingerprint. The inclusion of the microspheres was also shown to have no effect on the reactivity of the reactor system, even with 50 microspheres in each pebble. It was demonstrated that ultrasound waves can penetrate graphite to image the configuration of microspheres with a resolution of 300 – 400 µm. Although a better resolution is preferred, the resolution of the imaging system can be sacrificed if the number of microspheres is increased. One limitation in the imaging experiment was the absence of TRISO particles in the gelatin phantoms. Future work should optimize the system by imaging samples that embed the microspheres and TRISO particles within graphite. Finally, it was shown that while the previously proposed hybrid safeguards approach can adequately detect the abrupt or protracted diversion of material from a single reactor, the system does not have the ability to detect a protracted diversion spread across multiple facilities. The microsphere fingerprint verification however, was shown to be capable of detecting such a protracted diversion. This ability to detect the actions of an adversary across multiple facilities over an extended period of time demonstrates the great potential the microsphere fingerprint verification system would have in safeguarding a PF-HTGR facility.

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Development of Analytical Instruments for Prediction of Nuclear Terrorist Activities

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Introduction

Creation of nuclear weapons, proliferation, and accumulation of large stocks of fissile materials in several states led to the emergence of a new threat—nuclear terrorism. In turn, nuclear terrorism is inseparably linked with the expansion of the scope of terrorist activity and intensification of subversive actions on the part of various extremist and fundamentalist religious groups that are considering this kind of terror as a powerful tool to achieve their goals.

The presence of different nuclear materials in about 450 industries, as well as at hundreds of research reactors, tens of thousands of nuclear warheads, and a number of various facilities combining infrastructures in more than thirty countries, creates objective prerequisite for the expansion of criminal activities and for the spread of possible acts of terrorism in this extremely sensitive area of the global community. The situation is also aggravated by the fact that hundreds of thousands of professionals, personnel, and support staff are involved in nuclear field activities.

In addition, the amount of nuclear material (NM) necessary for an act of terrorism, which may lead to horrible consequences with large human and environmental impacts, is relatively small. This fact makes such materials most attractive for terrorist groups. All of the above factors increase the vulnerability of nuclear field protection systems to terrorist attacks. Therefore, along with NM management and accounting, another important task is development of additional analytical instruments that might be helpful in predicting terrorist actions and in the determination of crucial points of present protection and security systems. This article discusses the approach to creating such instruments.

Presumptive Types of Nuclear Explosive Devices that Nuclear Terrorists Might Choose

Nuclear device types that terrorist might choose depend on their goals, capabilities, and resources (mainly on nuclear and radioactive material resources). In turn, targets are limited by the nuclear device types that terrorists can produce or/and by the kind of material they have obtained.

In this work, we consider four main types of nuclear devices that can be used by terrorists. The first is a nuclear bomb, more formally known as improvised nuclear device (IND). The second is a radiological bomb or radiological dispersal device (RDD).[1]

The third type of nuclear device contains an aqueous solution of fissile material at a ratio sufficient for fission chain reaction to occur, called a self-sustained chain reaction device (SCRD). Over the past sixty years there have been several incidents with nuclear material solutions at the nuclear fuel cycle (NFC) industries.[2] The mechanism on which such incidents proceeded, can be used by terrorists for SCRD creation. In addition, some critical parameters of uranium salt solutions are available in open sources.[3,4] Therefore, in our opinion particular attention should be paid to this type of device in nonproliferation studies because of its potentially simple design and scale of possible consequences from its actuating. By design, an SCRD might be a small vessel, e.g., in the form of sphere, with a fissile material solution inside it, which becomes critical at a certain concentration ratio, producing an extremely dangerous neutron pulse. When properly designed, such a device can act for several hours with a recurrent fission chain reaction, thus increasing the threat of its implementation. Moreover, there is also the possibility of its detonation with a release of a sufficiently large amount of energy equivalent to the explosion of tens of kilogram trinitrotoluene (although in this case the SCRD would not be a nuclear bomb in the usual sense), which would, in turn, lead to massive destruction. The calculations we have made show that the radiation dose near crude SCRD devices can reach 500 rad/s with a corresponding neutron flux of about 10^{16} n/cm^{2}s, which is in agreement with the data of other authors.[3]

The fourth type of nuclear device is an irradiation device. This device may be a container filled with a highly radioactive substance, for example Co-60. Located in a crowded area and well camouflaged, an irradiation device may cause significant harm to human health and the environment before it is detected. Furthermore, the scale of such an action depends on the location of its application. Such devices have already been used by terrorists, resulting in significant harm to human health and economic impact.[5]

Each type of nuclear devices has its own "damage capability." The most destructive and therefore most attractive type for terrorists is IND. However, it contains high-tech elements and it is the most complicated to manufacture, especially for non-professionals. A device with fission material solution is less hazardous and much simpler to manufacture but it also requires specific knowledge from nuclear field for handling and actuation. Possible consequences from applying RDD are much lower than from other types but it is simplest for construction and transportation. An irradiation device is also relatively easy to use (though, of course, it requires radiation protection), however, in terms of radiation influence on humans we can place it between SCRD and RDD.

Thereby, we can class the different devices by descending "demolition power": improvised nuclear device (IND) > self-sustained chain reaction device (SCRD) > irradiation device > radiological dispersal device (RDD). Demolition power can be measured as economic loss, casualties, or psychological damage such as chaos.

Necessary Nuclear Material

Nuclear device type selection, as it already has been said, depends on the motivation and resource base of the terrorists. Today in the world, there is a sufficiently large amount of fissile and radioactive materials that could be used to construct one of the aforementioned devices. According to the report of the International Panel on Fissile Materials, highly enriched uranium (HEU) global stock is about 1,500 tons, part of which (a few tens of tons) is in civil use. The amount of plutonium stock, accumulated during the years of nuclear power, is approximately 500 tons in separated form and more than 2,000 tons as a part of spent nuclear fuel (SNF), and this value continues to grow.[6] In addition, there are a large amount of radioactive materials and radiation sources that can be used by terrorists. Accurate control and accounting of all these materials is a difficult task and therefore is not always effective enough. It is also possible to show that in certain cases a relatively small amount of NM might be required even for manufacturing a nuclear explosive device (NED). For example, 10 kilograms of 90 percent enriched uranium is enough to make a critical mass. In the case of plutonium, critical mass might be much smaller even if reactor-grade plutonium (instead of weapons-grade) is used. Figure 1 shows critical mass—nuclear fuel burnup diagram for a sphere made of plutonium extracted from various nuclear power plants (NPP) spent fuel and surrounded by a beryllium reflector. This diagram was calculated using MCNP code (burnup data was taken from the Nuclear Energy Agency Web site.[7] It can be seen that critical mass for a plutonium sphere is approximately two times less than for a uranium sphere even at high burnups. Despite the difficulties in handling reactor-grade plutonium (it is a very radioactive and toxic material) and less explosive power compared to a uranium bomb (because of higher spontaneous fission rate for plutonium), radiological consequences from the activation of such a device could be devastating. The least amount of fissile material is required for manufacturing of an SCRD—about 0.87 kilograms of 90 percent enriched uranium dissolved with water in certain proportions can produce a SCRD.[3,4]

In other words, there is a sufficiently high possibility for terrorists to create and apply a nuclear device if they can acquire fissile materials (even in small amounts). Therefore, it is necessary to perform a system analysis to study the possibility of nuclear terrorist acts and to promote actions for prevention of such terrorist acts on the basis of this analysis.

Analytical Approach for Prediction of Nuclear Terrorist Activities

The approach to developing analytical instruments used in the present study is based on event trees, which are used in the nuclear safety analysis of nuclear reactors and nuclear power plants. The analytical instruments considered within this paper are more accurately defined as "prerequisite trees," but they have a similar logic of construction. An event tree includes one initial event and a set of finite events diverging from it. A prerequisite tree includes a single main event and a set of prerequisites that converge to it (Figure 2).

It should be noted that in this paper, a prerequisite tree is considered primarily as a tool for developing indicators. In the next phase of work it will be possible to analyze the tree quantitatively by assigning an appropriate weight to each of the indicators. However, issues related to the definition of these weights have not yet been considered, since the full set of indicators must be determined first.

While constructing a prerequisite tree, the final event of which is a terrorist act with a nuclear device application, it may be possible to identify specific indicators that can allow detection in the early preparation stages and thus assist in prevention. Therefore a goal of this study is to develop a set of these indicators, define sources of information necessary to detect them, and set signal thresholds that will generate corresponding law enforcement actions.

The following classification of nuclear terrorism is usually defined in articles devoted to the problems connected with it:

- Theft of a nuclear warhead and its deployment
- Theft of NM and manufacturing of IND and/or SCRD
- Theft of radioactive materials and manufacturing of an RDD for further spraying by means of explosives
- Sabotage or capture of a nuclear facility with the intent to cause an explosion, followed by release of radioactive material (such as the seizure of a nuclear power plant to implement the reactor beyond design parameters, causing a nuclear accident)

In this work we have considered two of these cases—actuating a nuclear device and manufacturing one with fissile or radioactive materials.

Figure 1. Critical mass — fuel burnup diagram for reactor-grade plutonium sphere with beryllium reflector

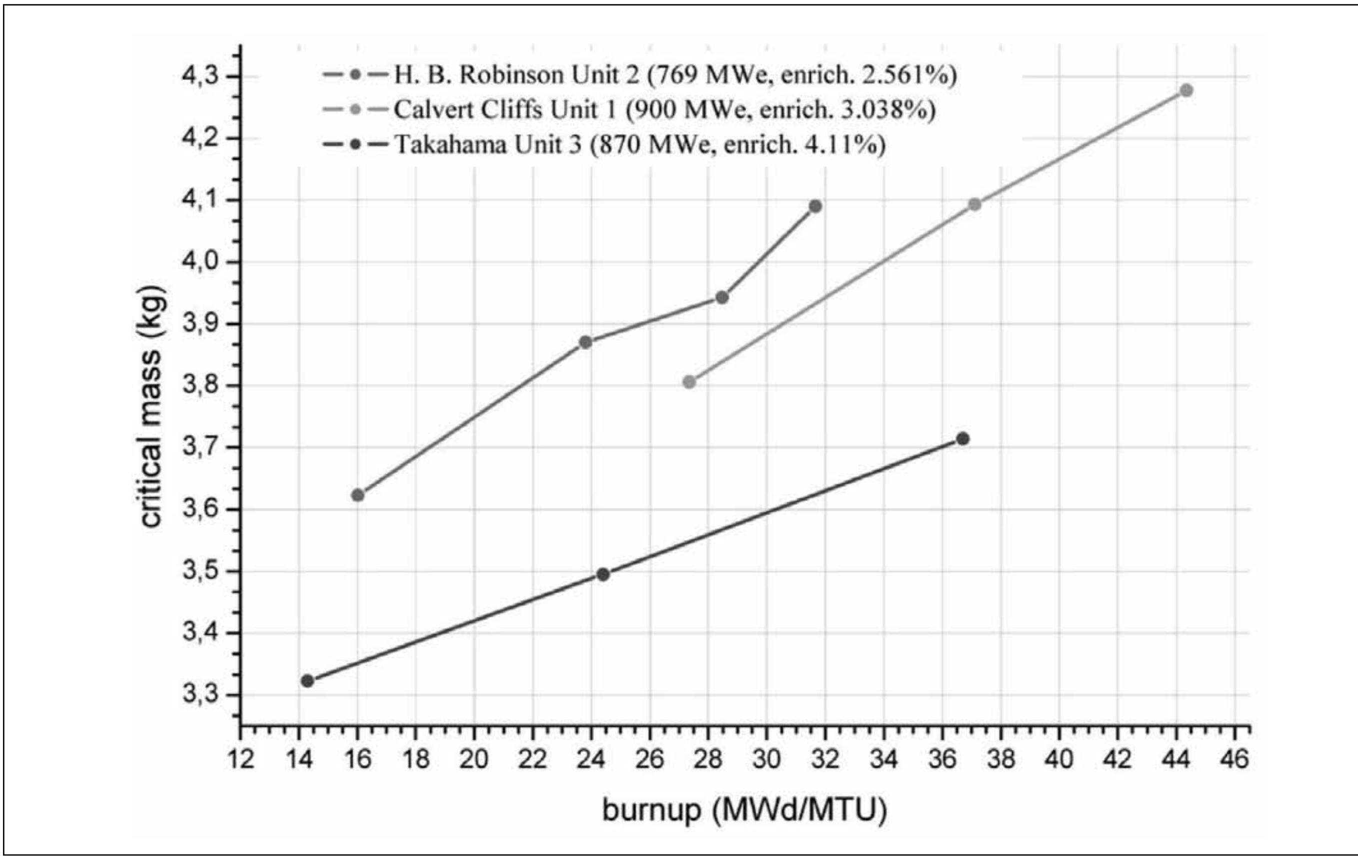
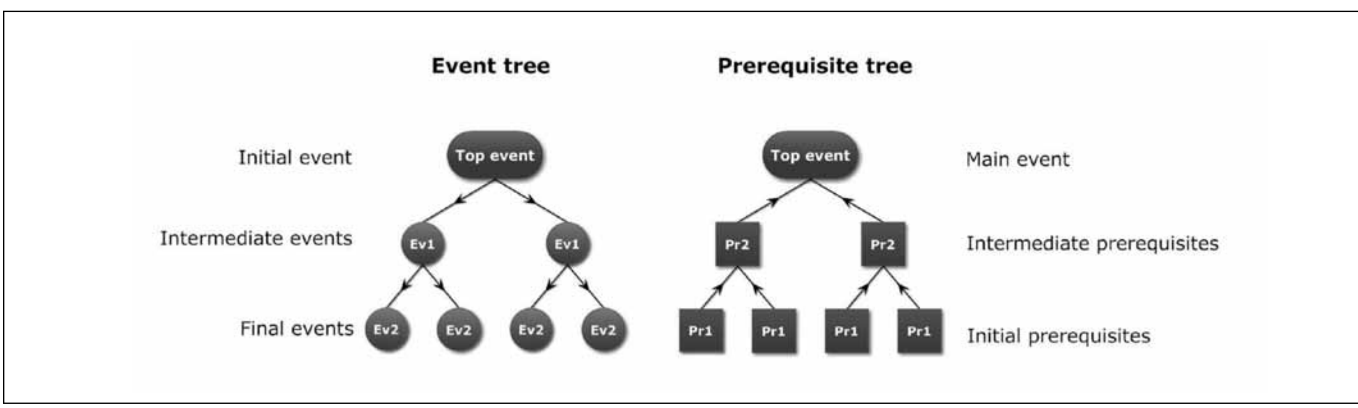


Figure 2. Event tree and prerequisite tree group differences

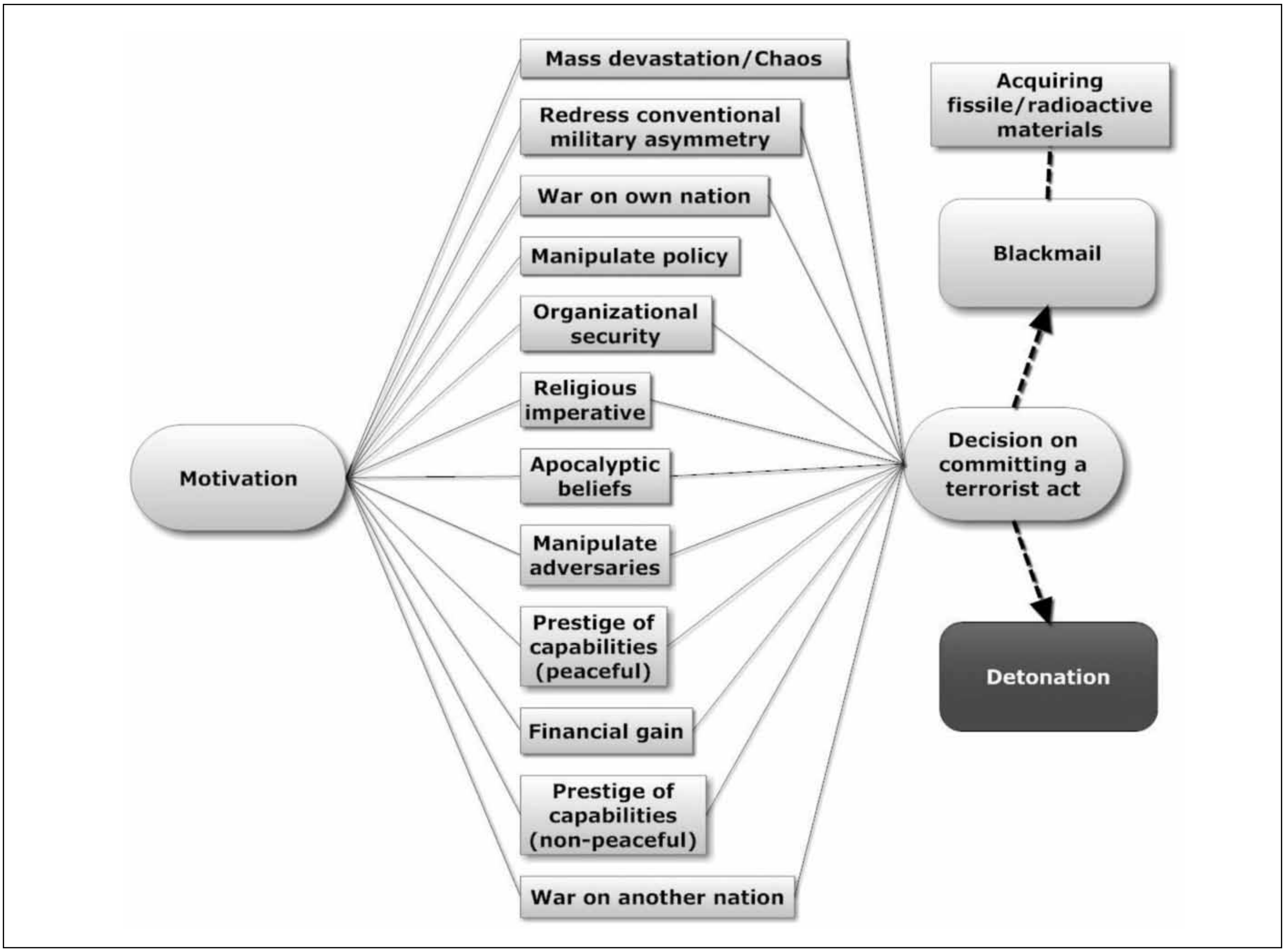


Main Tree and Motivation Branch

The main (top) event in the constructed prerequisite tree is detonation of a nuclear explosive device (NED). It divides the tree into two parts: the motivation of a terrorist group, and the main tree, which includes the resources and phases necessary to achieve the top event.

Motivation, as well as the scale of destruction, depends on the size of armed groups. Well-known and powerful terrorist organizations, such as Al-Qaeda, are likely to have enough resources to implement the most extreme case with maximum damage—actuating of IND. Meanwhile, for small groups most probable top event will be creation of RDD or SCRD, or merely blackmail. Motivations of terrorist groups have been already reviewed.[8] This list of motivations is sufficiently complete, however we have added one more item—"financial gain" (Figure 3)—because there have been cases of terrorist attacks where the aim of terrorists was to obtain financial gain.[9] Thus, a wide range of threats is taken into account within this prerequisite tree. They may come

Figure 3. Terrorist group motivations



from terrorist groups, completely different in their structure, size and objectives.

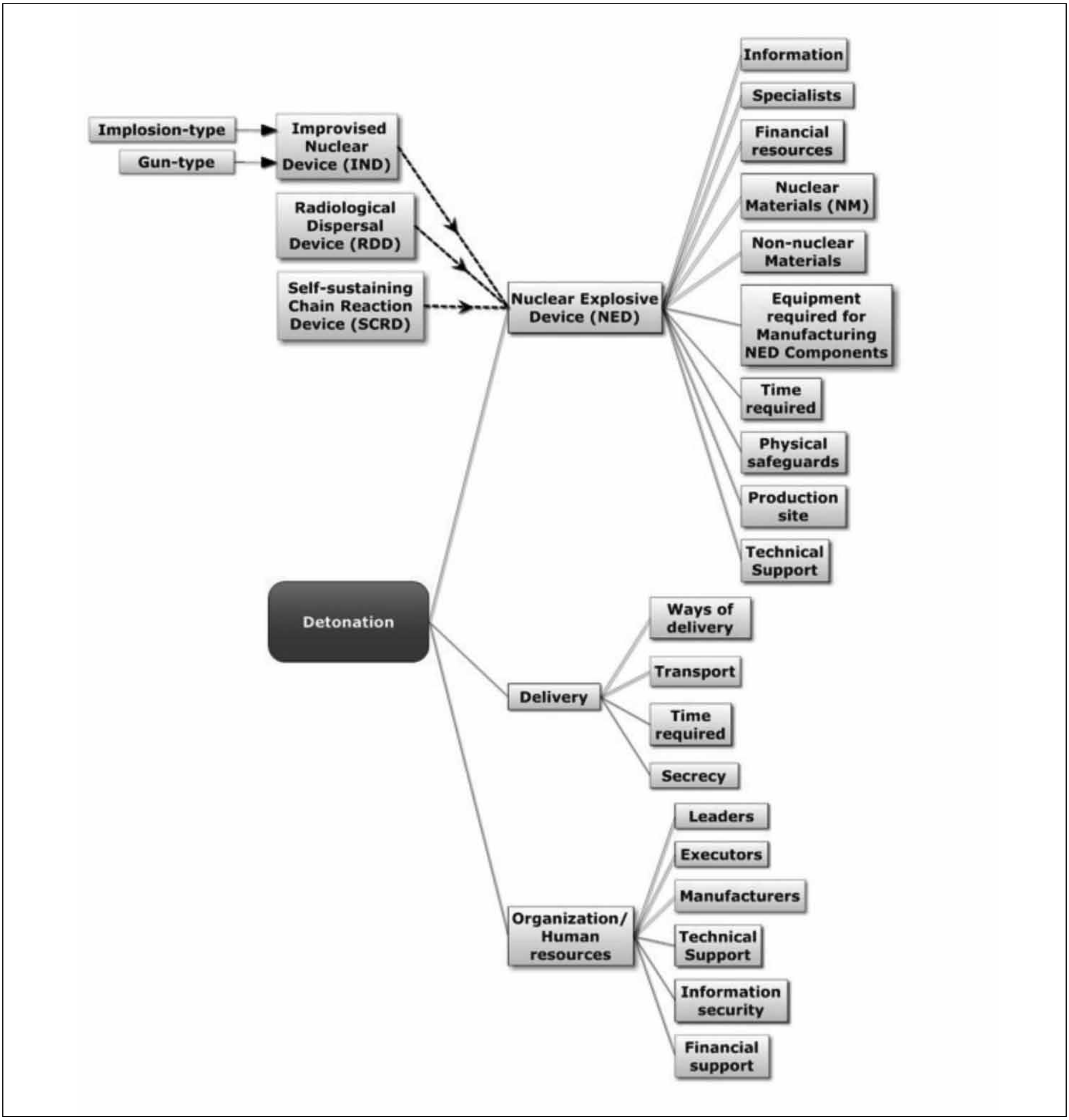
Certainly the more global the motivation of terrorists the more powerful the weapons they can seize. Therefore with IND they can follow any of the listed motivations. At the same time, for RDD and SCRD the most probable elements of the "motivation" branch are "mass devastation," "manipulate policy," and "financial gain." Terrorists' requirements (if they are declared), representing their motivation, can be device type indicators themselves.

The main tree (Figure 4) has three basic branches: the "nuclear device," its "delivery" and "human resources/organization." They, in turn, include sub-branches, the keys of which are: "information," "specialists," "nuclear/radioactive materials," and "financial resources." By analyzing mostly these parts of the tree, special indicators can be produced, which is the easiest way to trace nuclear terrorists activity. Elements connected with security and secrecy of terrorist actions are also of great importance. These items can lead to disclosing of malefactors' plans irrespectively from other branches.

Information Branch

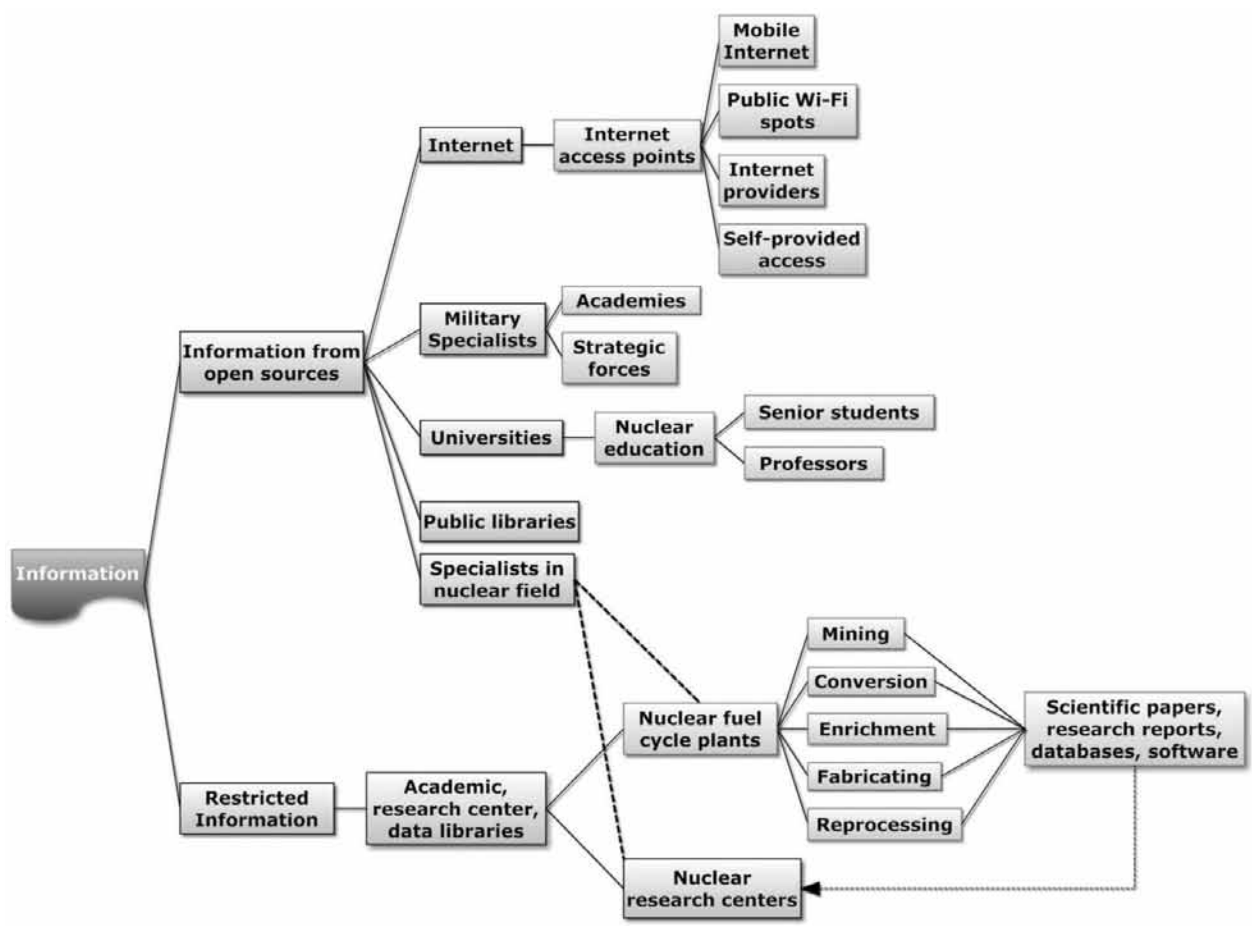
Information source analysis is rather significant for timely detection of nuclear terrorist activity. Such specialized know-how as nuclear device construction is difficult to come by. It requires a relatively large amount of knowledge and skills. Ways of obtaining this knowledge are considered in branch "Information" (Figure 5). At present, information from the nuclear field is widely represented in open sources, first of all on the Internet. Another source of information: professionals and technicians, workers of educational or scientific institutions, and NFC industries. It is worth noting that educational institutions provide theoretical knowledge while industrial enterprises provide practical knowledge. Manufacturing of nuclear explosive devices similar to IND or SCRD is impossible with only one of these information types.

Figure 4. Main tree



In this tree, information is divided into two parts—information from restricted sources and information from open sources. The main difference between them is that open source information can be easily utilized by malefactors without any control from police. Therefore open sources are more vulnerable than restricted sources and require special attention. Unapproved access to closed specialized literature or the loss of same is also an indicator of nuclear terrorist activity.

Figure 5. Information branch



Financial Resources Branch

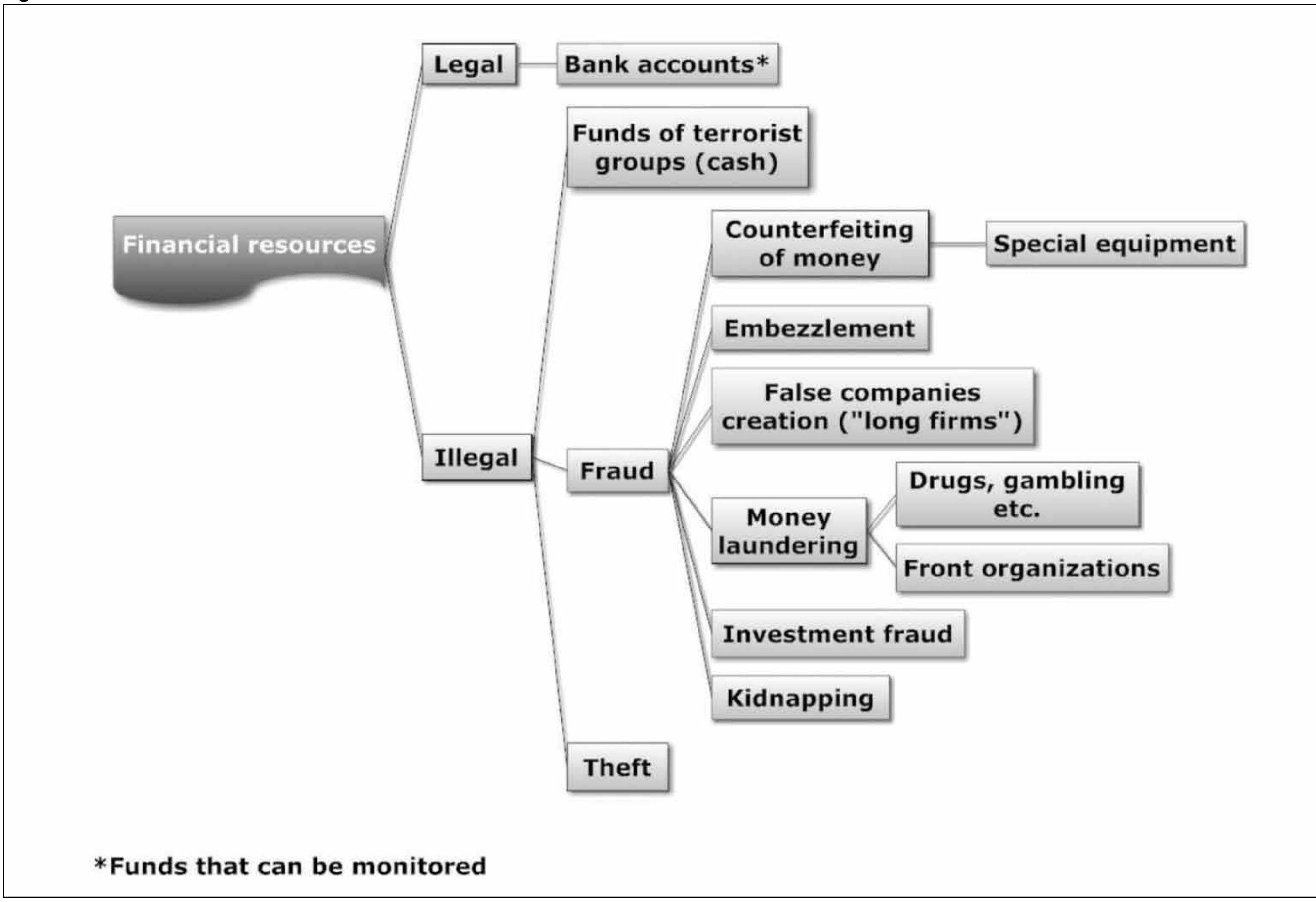
The branch of "financial resources" is one of the keys in the main tree, because the organization of NM acquisition or theft and the preparation of the technical base for manufacturing such a high technology product demands considerable financial resources. In this case, it is fair to believe that powerful terrorist groups have significant assets or financial sources, while small groups can hardly acquire NM in quantities sufficient for IND. In addition, indicators based on this branch can allow detection of terrorist activities much earlier than using other indicators.

Financial streams in this tree are divided into legal and illegal. Legal is much easier to trace than illegal. Indicators of this branch are based on financial violations. Illegal sources of the finance in itself are criminals—whether by embezzlement of funds in large amounts or fraud (Figure 6). It is necessary to use information about where this money has been spent. In legal financial streams it is necessary to pay attention to the movements of money in large quantities if their purpose is not clear. Financial violations may also include recently created organizations with suspicious activities. Such an organization can conduct transactions, for example purchasing nuclear materials or specialized equipment, ostensibly for medical purposes. Behind such firms there can be terrorist groups and consequently it is necessary to concentrate special attention on them. Thus, by means of control over financial streams, namely having defined special indicators for this branch, it is possible to detect preparations for an act of terrorism at the early stages.

Nuclear Materials Branch

NM acquisition would be the most complex and challenging operation for any terrorist group to perform in nuclear terrorism activities. The nuclear and/or radioactive material branch (Figure 7) represents a set of the stages necessary for the acquisition of the basic driving or blasting part of a nuclear device. Such materials may be stolen during transportation or obtained from nuclear

Figure 6. Financial resources branch



fuel cycle industries, specialized hospitals, and radioactive waste disposal sites. We also should not exclude the probability of the acquisition of nuclear or radioactive materials through the so-called black market.

The disappearance of NMs attractive to terrorists from NFC industries, as well as the level of their background radiation and characteristic energy peaks, can serve as indicators. For example, a well-known characteristic of cobalt-60 is its gamma-ray radiation energy peak of 0.6 MeV. This feature and other methods of spectrometry can serve as a tool for police in determining the type of nuclear device and its location.

It is also necessary to take into consideration the case when an employee of an NFC industry steals NM and conceals its loss. In this scenario a theft might not be detected immediately and the time for the adoption of corresponding measures would be wasted. This creates a complexity for timely detection of terrorist activity. However, the amount of time between the theft and the detection of theft can be used as an indicator of probable progress in NED manufacturing.

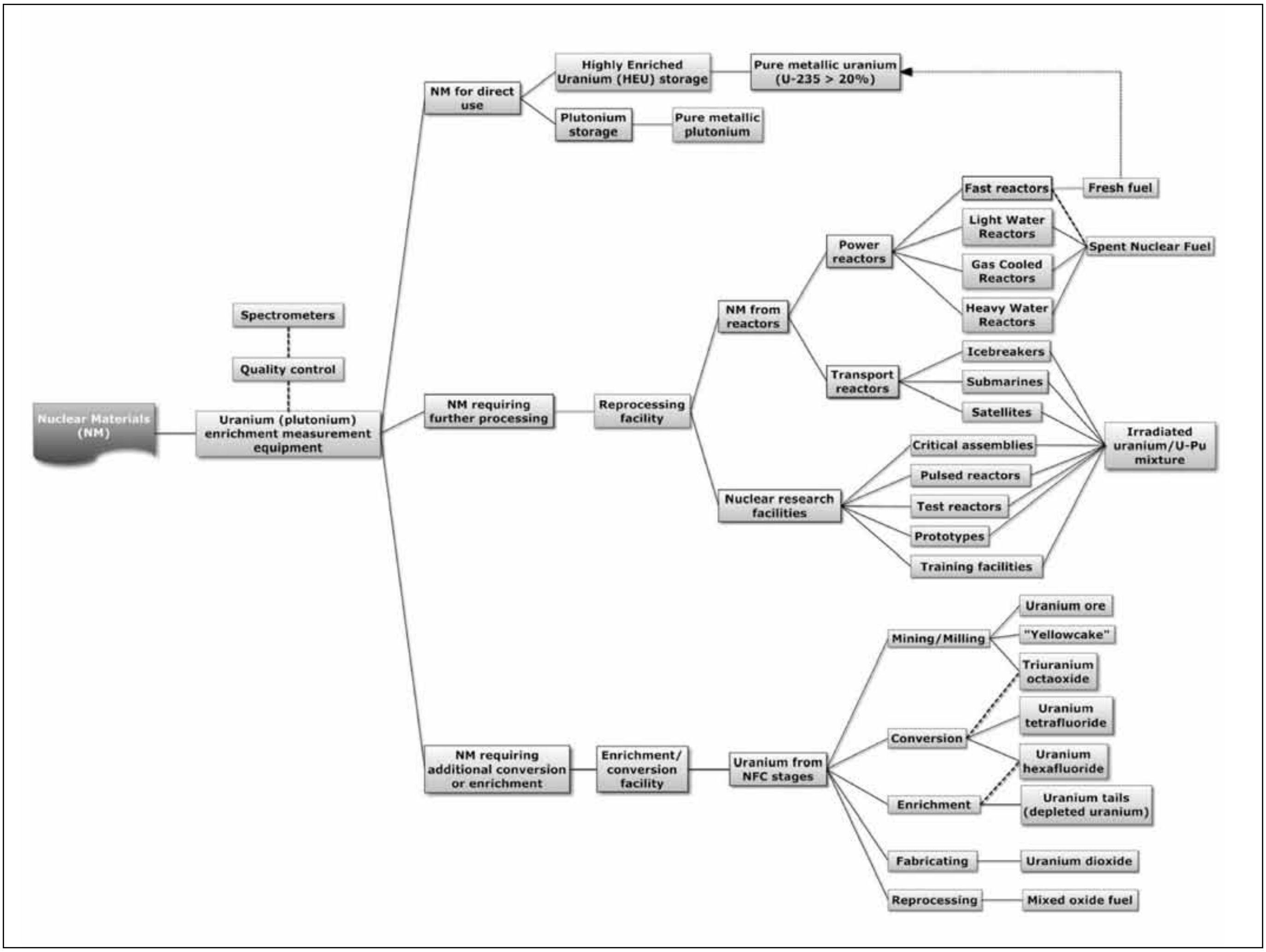
Due to the possibility of using low-enriched uranium for SCRD creation, the range of sites from which NM can be obtained is greatly increasing, as compared to other types of such devices. Therefore, despite the necessity of the possession of some knowledge in nuclear fields, the relative simplicity of SCRD manufacturing coupled with the scale of possible consequences makes it perhaps the most dangerous along with IND and RDD.

Delivery Branch

NED delivery to the site of a possible terrorist attack is the last stage before the top event of the tree (Figure 8). Determination of the nuclear terrorists' activity at this stage means that prevention of NED production has failed.

The choice of delivery method by terrorists depends on many parameters. First, it depends on the type of device. Second, it depends on accessible types of transport in the given district. Finally, it depends on the capabilities of malefactors to seize the required transport. The common factor for all methods of delivery is that it would be done by means of vehicles. Moreover, it will be realized with the use of relatively large vehicles, due to the activity of the device, its dimensions and weight. It is difficult to say what will be the most suitable for attackers. Therefore, the indica-

Figure 7. Nuclear materials branch



tors in this branch—as well as in the NM branch—include the level of background radiation and its spectroscopic monitoring.

Conclusion

This article presents an approach that allows analysis of the prerequisite of terrorist activities at all stages, from the motivations of malefactors to the actuation of a nuclear device. As a result, the approach is a prerequisite tree, which at present is equipped with only those branches which should initially be taken into account.

With additions from specialists, for example from the banking or IT fields, the tree can be expanded, thus obtaining a universal analytical tool for preventing terrorist acts involving nuclear devices.

Also the potential of nuclear devices has been analyzed in this work, which gives a representation of possible threats from intruders. Depending on the type of device under consideration, the tree has specific features and modified branches. Tree analysis can identify vulnerabilities in the terrorists' actions—the so-called special indicators, examples of which are also presented in this paper.

Future work should focus on expanding the tree using a more detailed set of indicators. This, in turn, can be used by law enforcement agencies to prevent acts of nuclear terrorism.

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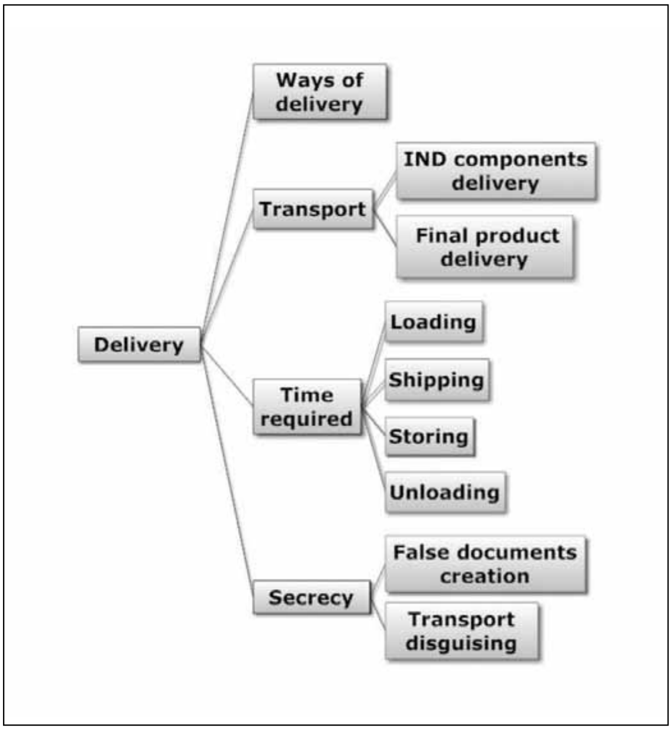
Figure 8. Delivery branch



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MCNPX-PoliMi Post-processing Algorithm for Detector Response Simulations

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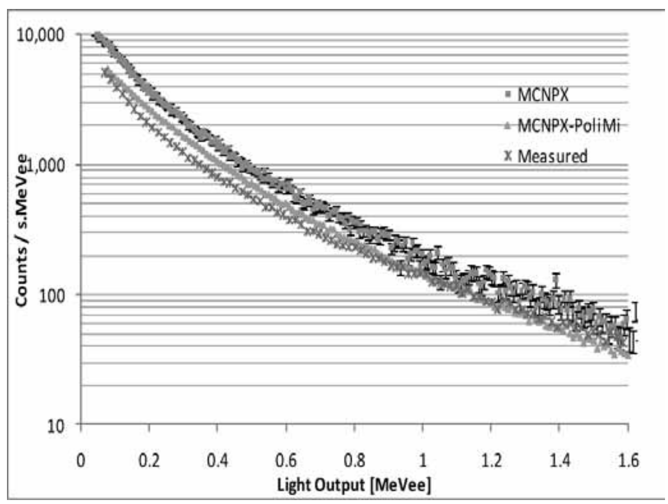
Abstract
In the field of nuclear material detection and characterization, Monte Carlo simulations provide valuable insight into complex radiation transport problems. However, in many applications, it is the detector response that is desired. MPPost is a FORTRAN program that has been developed to interpret the results from the Monte Carlo code MCNPX-PoliMi and return a realistic prediction of the detector response. This program is an enhanced version of an earlier MCNP-PoliMi post processor written in Matlab.[1] The conversion to a FORTRAN based algorithm allows MPPost to process much greater volumes of data that would be impossible to handle with a Matlab based equivalent. This paper describes the development of MPPost and outlines its capabilities.

MPPost was designed specifically for the MCNPX-PoliMi data output file. This file consists of a comprehensive list of collision events that occur in each detector cell. The MPPost program uses this summary of collision events to model the response in a detector volume. By characterizing the response of a detector with empirically determined parameters, accurate simulation of the detector response is obtained. In addition, the program can perform several common analysis techniques. These are described in this report.

Introduction
MPPost was developed to bridge the gap from the simulation of particle transport to the simulation of a realistic detector response. The release of this program will greatly enhance the capability of MCNPX-PoliMi to simulate detector response. Users will be able use the program to quickly generate detector responses. A user input file will allow the user to customize the simulation parameters to more accurately simulate a particular application.

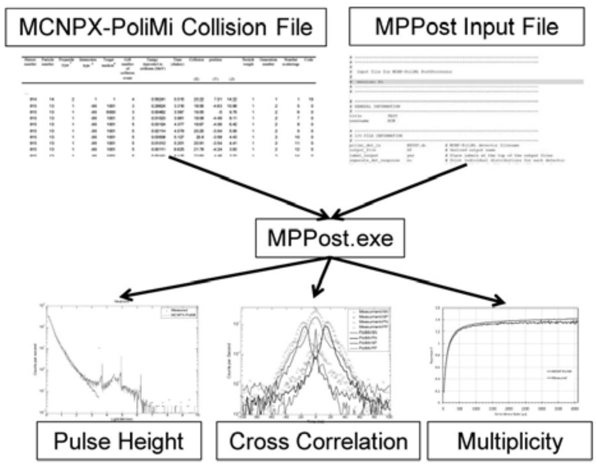
The ability of MPPost to quickly and easily generate a wide variety of simulation results allow it to be applied to a diverse set of problems. MPPost was used to simulate cross-correlation distributions to help in planning measurements of MOX fuel in Ispra, Italy.[2,3] The simulation was used to quickly determine the best source detector distance, and provide an estimate of the amount of data that was expected.

Figure 1. Neutron pulse height distribution simulated with MCNPX-PoliMi/MPPost and MCNPX, compared to a measurement of a 2.9×10^5 n/s ^{252}Cf source using an EJ-309 liquid scintillator



MPPost was developed to work with MCNXP-PoliMi to take advantage of information provided in a user-specified file. This file contains all the necessary information relevant to recreating the detector response (dead time, response curves, energy resolution functions, etc.). A more accurate simulation of the detector response is made possible by the information contained in the detailed collision information provided by MCNPX-PoliMi. Figure 1 shows a pulse height distribution for a 2.9 $\times10^5$ n/s ^{252}Cf source measured with an EJ-309 liquid scintillator simulated with MCNPX-PoliMi and MPPost compared to one simulated with MCNPX. The MCNPX result was determined by transforming the result of an F8 tally by using a combination of light production functions characterizing the light production from interactions on hydrogen and carbon. These functions were weighted based on the ratios of events on these elements in the detector volume. The MPPost result shows better agreement with the measured result.

Figure 2. Schematic of the performance of MPPost



Currently, MPPost is capable of simulating the response for liquid and plastic organic scintillators, NaI, CaF_2, $LaBr_3$, and ^3He detectors. There are plans to expand this capability to encompass other common detector types. In addition to calculating the detector response, the MPPost is also capable of simulating common data analysis techniques such as time-of-flight, cross-correlation, and neutron multiplicity. These capabilities are also being enhanced to incorporate other techniques such as back-projection imaging and liquid scintillator multiplicity analysis.

Due to the diverse array of detector types and processing methods available in the field, MPPost is designed to be highly modular so that new techniques and detectors can be easily incorporated. A generalized schematic of the program is shown in Figure 2.

The program is separated into two general sections based on how the pulses are generated in the detector. The first section processes scintillation detectors and the second handles ^3He detectors.

Scintillation Detectors

Organic liquid and plastic scintillators are good candidates for the detection of fast neutrons and photons from fission; they have been applied in a number of measurement systems for detecting and monitoring nuclear materials. The MCNPX-PoliMi collision log contains information such as type of interaction, with which nuclide the collision occurred, time of interaction, and the energy deposited in the event. Using this output, it is possible to recreate the response of a detector.

The primary difference between the types of scintillation detectors is their light generation properties. By modifying the light conversion parameters MPPost is able to recreate the response for multiple types of scintillation detectors at once. The process for handling the production of light in a detector is outlined below.

Light Production – Organic Scintillators

The simulation of scintillation detector pulses requires that the energy deposited in the detectors by neutrons and photons is converted into light output. Typically this is done using measured detector response functions. Photons are detected primarily by Compton scattering, and the energy-deposited-to-light-output response is linear by definition:

$$L = gE_\gamma \tag{1}$$

where E_γ is the energy deposited by the photon (MeV), L is the measured light output (MeVee), and g is the energy-to-light coefficient in (MeVee/MeV). For photons the coefficient is very close to 1 MeVee/MeV.

Neutrons are detected primarily by elastic scattering on hydrogen. The neutron-energy-to-light-output response functions were initially measured[4] for liquid (BC501) and plastic (BC420) scintillators. The measured light output functions were assumed to pass through the origin; that is, E_n=0 corresponds to a light output L=0. The measured response function fit the following quadratic function for the liquid scintillator:

$$L = mE_n^2 + nE_n \tag{2}$$

where E_n is the energy deposited by the neutron on hydrogen (MeV) and L is the measured light output (MeVee). The coefficients m (MeVee/MeV^2) and n (MeVee/MeV) are detector-dependant parameters. For example the liquid scintillator BC501 has coefficients m=0.035 and n=0.1410. Coefficients for a common plastic detector are m=0.0364 and n=0.125.[4]

In order to accommodate further investigations of the functional form, the equation has been expanded to a fifth order polynomial.[5] These investigations focused on the energy-to-light conversion in EJ-309 liquid organic scintillators have found the improved results can be obtained using both higher order polynomials and/or non-zero intercepts. Current efforts are under way to investigate more robust and physically based coefficients to further improve agreement. Establishing the ideal coefficients is an area of ongoing research. Currently the functional form implemented in MPPost for the light produced from a collision with hydrogen is:

$$L = aE_n^4 + bE_n^3 + cE_n^2 + dE_n + f \tag{3}$$

The coefficients a through f can be controlled by the MPPost input file and can be adjusted for a specific scintillator type and detector design. For the most accurate simulation results, a unique set of coefficients for each detector type and design should be obtained, usually by measurement. This approach helps take into account detector-specific characteristics such as light collection.

Neutron interactions with carbon are assumed to generate a small light output with the same form as Equation 1 where g=0.02 MeVee/MeV.

Figure 3 shows the result of the simulated neutron pulse height distribution for a ^{252}Cf source measured with an EJ-309 liquid scintillation detector compared with a measured result. These results show good agreement between the simulation and the measurement.[6] Further improvement on this agreement should be possible as the light coefficients are further improved for this detector.

Light Production – Inorganic Scintillators

Inorganic scintillators are assumed to be only sensitive to gamma events, which are handled as in Equation 1. All neutron events are ignored.

Pulse Generation

The detector pulse is generated by MPPost by transforming the energy deposited in the individual scattering events into light output using the detector-specific coefficients for interactions with each nucleus. To account for the ability of the photo-multiplier tube to resolve light from individual events that occur close in time, the light from events that occur in a user-specified time window are added together. The sum of the light output from all events in this time window is compared with a light output threshold to determine if the pulse is observed. This user-specified time window is referred to as the "pulse generation time." A typical setting for the pulse generation time is 10 ns for the scintillators used in the present applications.

In addition, it is also possible to incorporate a non-paralyzable detector dead time in which all events detected are ignored by the processing algorithm. This dead time is applied to each specified detector individually.

Time and Energy Resolution

To further improve results of a comparison between simulation results and measured data, the resolution of the detector must be taken into account. Detectors inherently introduce some level of energy and time broadening into measured results. To help account for this, and to improve the results of the simulation, resolutions for various detectors were incorporated into MPPost. These energy resolutions are based on previously published results.[7] For each type of detector there is a functional form of the energy resolution with parameters that can be modified from the input file. Figure 4 shows the difference in the simulated spectrum of a ^{137}Cs source compared to the measured, with and without the energy broadening option in Reference 8. The deviations that are still observable are likely attributed to the uncertainty in the source strength of the ^{137}Cs source used in this measurement.

Figure 3. MCNPX-PoliMi simulated and measured 252Cf neutron pulse height distribution (EJ-309 liquid scintillator)

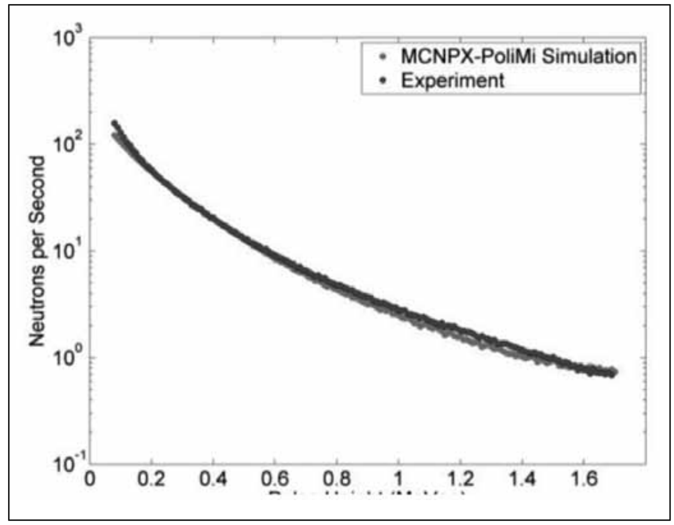
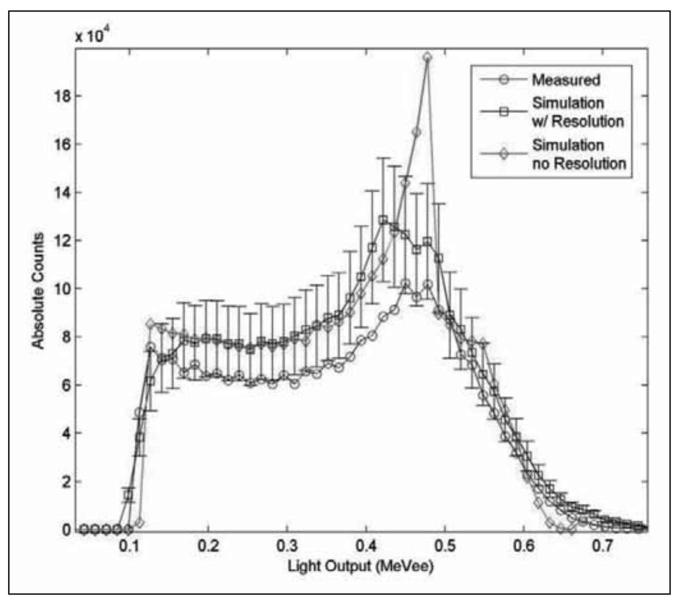


Figure 4. Simulated gamma-ray pulse height distribution of a ^{137}Cs source with and without energy resolution compared to a measured result

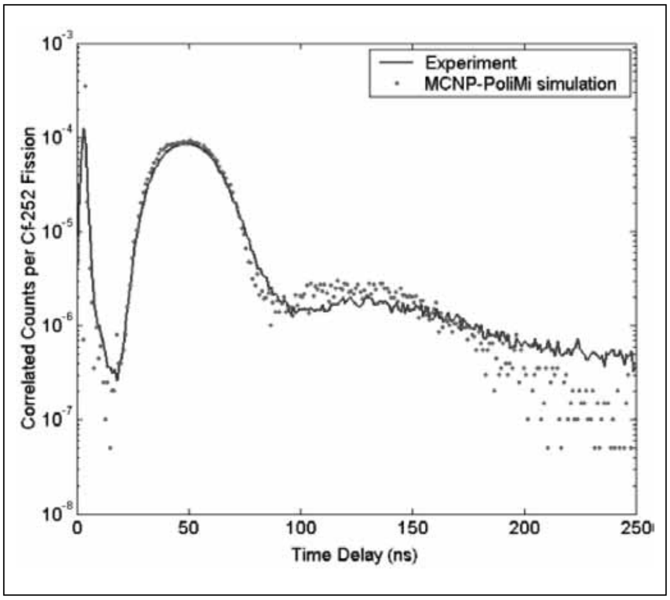


It is also possible to introduce time broadening. Each time that a pulse is detected, the time for that event is determined by the first contributing event in the detector. A Gaussian distribution with a user-specified variance about the true simulated time is sampled to obtain a time-broadened value.

Cross-Correlation and Time-of-Flight

Evaluating the arrival times of events in the detectors can provide valuable information about the source. MPPost is capable of gen-

Figure 5. TOF simulation for ^{252}Cf source compared to measurement



erating the idealized time-of-flight (TOF) for all detectors specified in the geometry. The TOF is ideal in the sense that a true time-correlation measurement requires at least two detectors. The first detector acts as a start detector, providing the time of the initial event. A second detector, or stop detector, provides the time that it took a particle released from the same event to travel the distance between the two detectors. MPPost is able to generate the ideal TOF distribution, where the start time of the particle is accurately known and an interaction in a start detector is not required. A TOF curve for ^{252}Cf measured with an EJ-309 detector is shown in Figure 5. Very good agreement is observed between the simulation and the measured result in the neutron region (30-100ns). At large times the deviation between the simulation and measurement is largely a result of geometry effects like room return. The under-prediction in the gamma-ray peak (around 3ns) is expected, some gamma-rays from decay events of daughters are not accounted for in the simulation. These gamma-rays will increase the total number of counted gammas as observed.

Another method of processing the arrival times of particles at radiation detectors consists of generating time-dependant cross-correlation data. Cross-correlations look for events that arrive in multiple detectors within a short window of each other, typically within 100ns, approximately. This technique is exceptionally useful when the detectors used are liquid scintillators. This allows for the incident particles to be separated by both timing and particle type, thus providing considerable information about the source, such as source position and detector timing properties. A variation of this approach allows the user to simulate a realistic TOF measurement using two or more detectors.[9] An example of cross-correlation distributions measured with two liquid scintillators for a ^{252}Cf source is shown in Figure 6.[2] This figure shows excellent agreement for

Figure 6. Simulated cross-correlation curve for a ^{252}Cf source compared to measurement

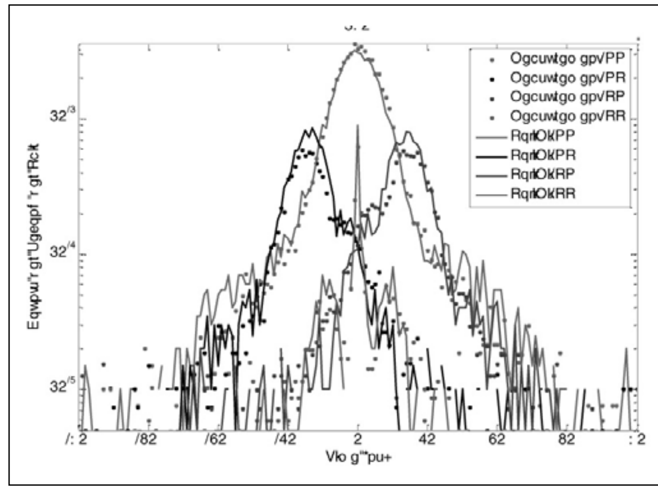
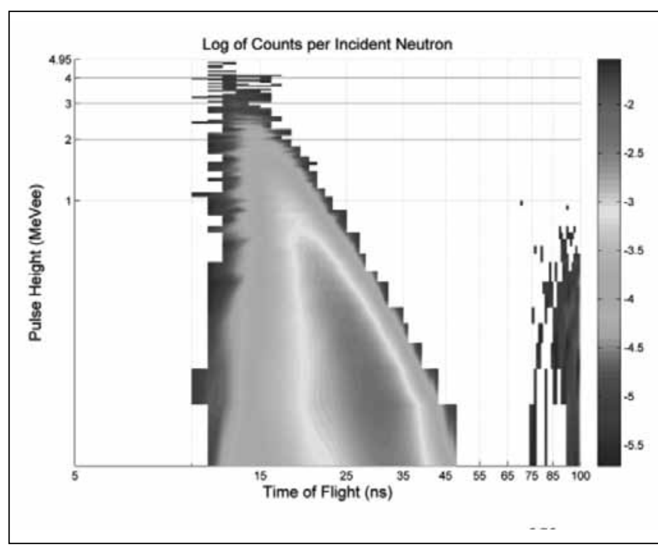


Figure 7. Pulse height-dependant TOF for ^{252}Cf, 50 cm from an EJ-309 detector



the (n,n) distribution. The (γ,γ), (γ,n), and (n,γ) distributions are slightly over-predicted by the simulation, but the overall agreement of the shape of this distribution is very good.

Pulse Height Correlation

In addition to separating detection events by their arrival time, it can also be useful to sort them by their pulse height. This approach generates a pulse height-dependant TOF distribution. MPPost is capable of generating both pulse height-dependant TOF and cross-correlation distributions for scintillation detectors. An example of a pulse height-dependant TOF is shown in Figure 7.

^{3}He Detectors

MPPost will also calculate the response of ^{3}He detectors. Due to the fundamental differences between scintillators and ^{3}He, both types of detectors cannot be processed at the same time.

For ^{3}He data processing, the MCNPX-PoliMi source must be distributed in time.[10] Due to the long time for the slowing down of neutrons, multiple neutrons from different source events can contribute to counts in the long time windows used in these systems. MPPost reads in the entire MCNPX-PoliMi collision file at once and then sorts the data in time. By selectively choosing only capture events on ^{3}He, a list mode set of detected events is generated. After an ideal list of detected events is collected, various dead time approaches can be applied. The first dead time option is a simple non-paralyzable dead time applied to each detector. The second options allow the user to specify a dead time for the ^{3}He detectors and additional dead times for up to two levels of electronics. An example of a system with two levels of electronic dead times in addition to the dead time of the detectors is an active well coincidence counter (AWCC). A schematic of this dead time is shown in Figure 8.

Once the accepted pulses are determined, the neutron multiplicity distribution, Feynman-Y, and the singles, doubles, and triples rates can be calculated.

Neutron Multiplicity Distribution

The neutron multiplicity distribution is a histogram that describes the observed frequency of detected neutron multiplets in the system in a given time window. There are two different approaches for how to establish these counting windows.

The first method is a constant window, in which a new counting window is opened immediately following the preceding window. Typical window sizes are on the order of a few microseconds to a few milliseconds. The number of multiplets is dependent on the size of the window; as the length of window increases, an increased number of fission events can overlap and contribute. Therefore it is possible to obtain multiplets with values much larger than the number of neutrons expected from a single fission event. The MPPost allows the user to specify a range of time windows to evaluate at one time. A schematic for this counting approach is shown in Figure 9. Figure 10 shows the comparison between the simulated and measured multiplicity distribution for a ^{252}Cf source using the constant window approach.[11]

The second approach is triggered windows. In this approach a new time window is opened only when an event triggers the system. A window is opened for each detected event and all events that follow this event are counted. Then the window shifts to the next detected event and all events in the window are counted. This approach continues until all detected events have been the acting trigger event. A schematic for this approach is shown in Figure 11.

Figure 8. Schematic of the electronics for an AWCC and the associated dead times

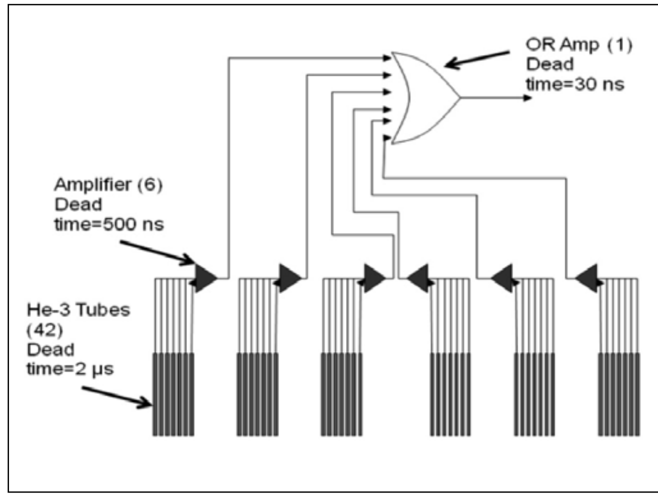


Figure 9. A schematic for constant window multiplicity counting

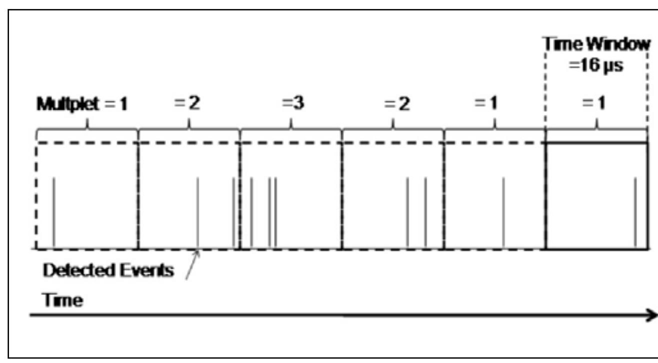


Figure 10. Comparison of the measured and simulated neutron multiplicity distribution for a ^{252}Cf source

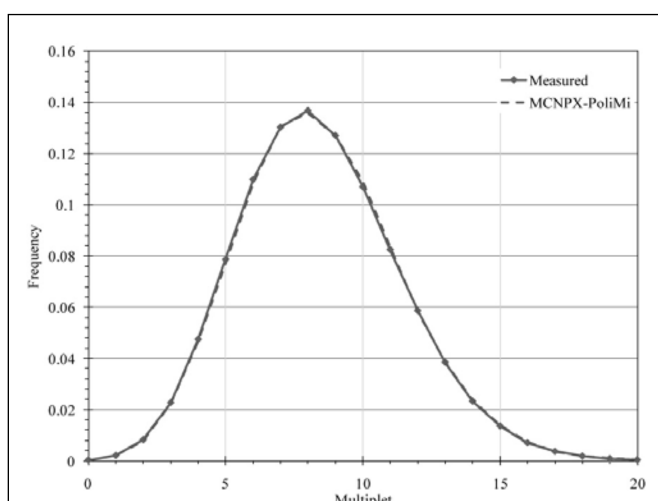


Figure 11. Trigger event approach for neutron multiplicity counting

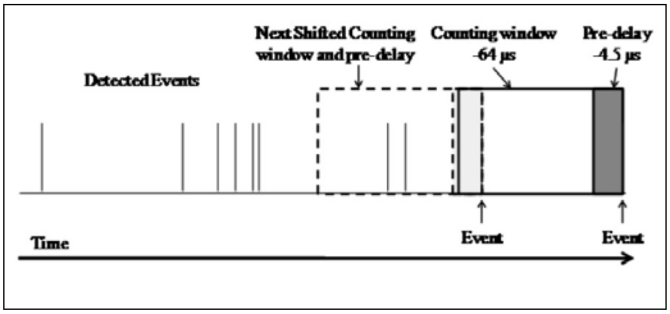
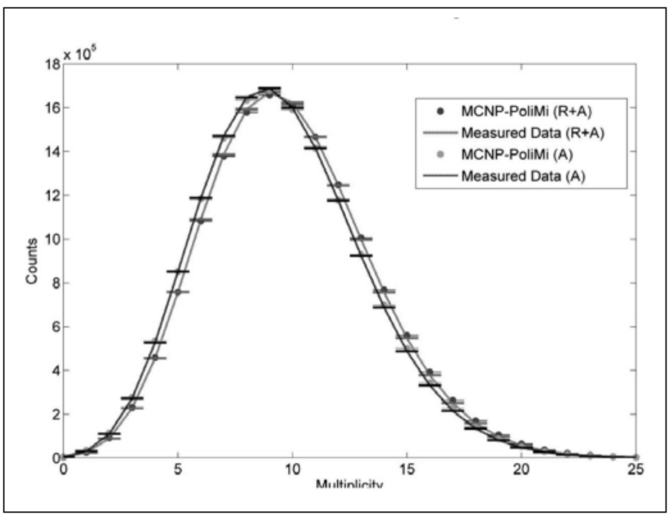


Figure 12. Comparison between simulation and measurement for the R+A and A distributions for a 252Cf source in an AWCC

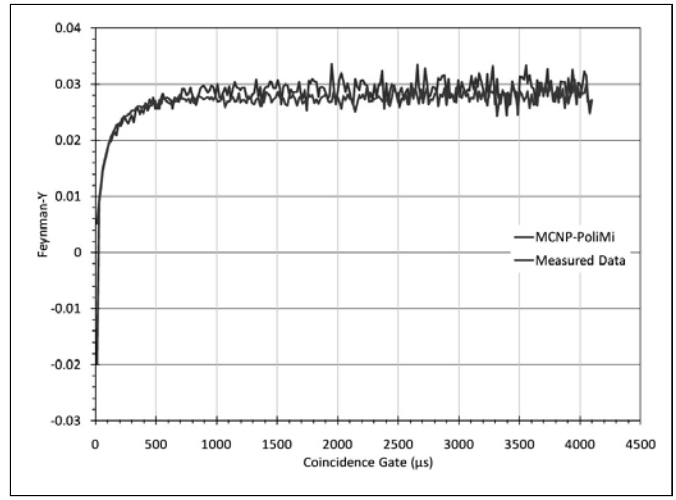


Accidental Distributions

When using the event-triggered window method for neutron multiplicity analysis it is useful to be able to obtain the distribution of the accidental (A) counts in addition to the real plus accidentals (R+A). To determine the accidentals distribution a second counting window is opened at a long time after the initial trigger event. This long delay is typically around 1,024 µs, but any value can be specified by the user. All events counted in this second window are considered to be accidental events. This provides both the signal distribution, R+A, and the accidental distribution, A. This distribution is used to calculate values for the singles, double, and triples rates. These rates provide useful information about a particular source.

Figure 12 shows a result of the trigger window approach comparing the R+A and A distribution to measured results for a ^{252}Cf source in an AWCC.[12] Excellent agreement for both the R+A and the A distributions can be seen in Figure 12.

Figure 13. Comparison of the simulated Feynman-Y to measured data for a ^{252}Cf source



Feynman-Y

Another metric used to analyze ^{3}He data is the Feynman-Y.[13] The Feynman-Y is defined as:

$$Y = \frac{\sigma^2}{\mu} - 1, \tag{4}$$

where σ^2 is the variance and μ is the mean. For a random source the neutron multiplicity distribution is a Poisson distribution, the mean and variance are equal, and the Feynman-Y is identically zero. As correlated events are introduced (i.e. fission events) the distribution of measured multiplets begins to deviate from that of a Poisson source, and the Feynman-Y increases.

MPPost will calculate the Feynman-Y for any neutron multiplicity distribution calculated. In addition, by automatically changing the window sizes within the program, the convergence of the Feynman-Y can be easily observed as shown in Figure 13.

Other Useful Features

In addition to the detector simulation capabilities outlined above, MPPost has additional features that allow the user to better analyze the MCNPX-PoliMi output.

Collision Event Log

This option provides the user with a complete summary of the events that occurred in the detector volume. The events are sorted by interaction type and by the nucleus with which the interaction occurred. This information is extremely useful for obtaining insight into the inner workings of the detector and good way to identify errors in the MCNPX-PoliMi input file. A sample output is shown below in Figure 14.

Figure 14. An example output of the event summary for a liquid scintillators detector

Summary of events in the Collison File

Detector: 10

Particle	Reaction Type	ZAID	Number
Neutron	Capture Event	1001	2104
Neutron	Capture Event	6000	38
Neutron	Elastic Scattering	1001	541381
Neutron	Elastic Scattering	6000	132436
Neutron	Inelastic Scattering	6000	181
Photon	Compton Scatter	6	179255
Photon	Compton Scatter	1	36335
Photon	Coherent Scatter	6	1820
Photon	Capture w/double fluorescence	6	198
Photon	Capture w/double fluorescence	1	3

Number of Scatters

MPPost will also outline the number of scatter events that contribute to a given pulse. This provides the user with a complete summary of the number of scattering events contributing to each type of detection, neutron, photon, or mixed. This information is very useful for optimizing the detector size for various applications.

Time-Dependent Mode

MCNPX-PoliMi has the ability to time distribute the source. If the source is not time-distributed all source events start at time zero. If the source is time-distributed then the source events occur over time, more realistically representing a true experiment. MPPost can adjust its processing to account for this. Normally the post processor handles each history individually, which provides a good approximation of the true behavior for most systems. However, it is possible for events from different source events (i.e., different Monte Carlo histories) to interact in a detector within a short enough time to contribute to the same detected pulse. To take this effect into account directly, MPPost can be run in time-dependant mode where only the interaction time of the particle is counted and the history number is ignored.

Summary and Future Work

MPPost is a FORTRAN program that has been developed to provide a wide array of detector processing options to the users of MCNPX-PoliMi. Current capabilities include the simulation of liquid and plastic organic scintillators, NaI, CaF_2, $LaBr_3$, and ^3He detectors. The program provides pulse height distributions for neutrons and gamma rays, time-dependent time-of-flight and cross-correlation analysis, and multiplicity distributions. This program greatly simplifies the simulation of detector response by including time and energy-dependent detector resolution functions and dead-time effects.

Efforts to release MPPost through the Radiation Safety Information Computational Center (RSICC) soon after the release of MCNPX-PoliMi are underway.

When this program is released it will greatly increase the ability of the MCNPX-PoliMi code to simulate detector responses. Users will be able to quickly generate accurate detector responses for a wide variety of detector systems, specifically those with applications in safeguards and nonproliferation. Other modules that are being investigated for inclusion in MPPost are a neutron and photon multiplicity routine for liquid scintillators as well as back-projection neutron and gamma-ray imaging.

Acknowledgement

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Roles for Process Monitoring in Nuclear Safeguards at Aqueous Reprocessing Plants

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Abstract

Process monitoring (PM) is increasingly important in nuclear safeguards as a supplement to mass-balance based nuclear materials accounting (NMA). The main goal for using PM in addition to NMA is to improve the ability to detect off-normal plant operation, which could indicate intent to divert special nuclear material. With this main goal in mind, programs within the U.S. Department of Energy and the National Nuclear Security Administration aim to advance the use of PM.

This paper reviews traditional PM roles, describes possible new roles, and then illustrates new PM roles using two diversion scenarios. Particular focus is on safeguards at aqueous reprocessing plants where in the particular case of solution monitoring, PM tracks frequent measurements of bulk solution mass and volume.

1. Introduction

This paper's focus is large commercial aqueous reprocessing plants. It is well understood that because nuclear material accountancy (NMA) measurement uncertainty increases as facility throughput increases, despite sustained efforts to reduce measurement uncertainty, it remains difficult to satisfy the International Atomic Energy Agency (IAEA) NMA-based diversion detection goal for large throughput facilities.

NMA at a declared and safeguarded facility involves measuring facility inputs, outputs, and inventory to compute a material balance (MB) defined as MB= $T_{in} + I_{begin} - T_{out} - I_{end}$, where T is a transfer and I is an inventory. The main quantitative assessment of safeguards effectiveness is the measurement error standard deviation of the material balance, commonly denoted σ_{MB}.

Partly in response to shortcomings of NMA alone, process monitoring (PM) is used as an additional measure to bolster NMA. While it is generally agreed that PM adds value to safeguards, its possible roles and benefits are not fully understood. The main goal for using PM in addition to NMA is to improve the ability to detect off-normal plant operation. Therefore, programs within the U.S. Department of Energy and the National Nuclear Security Administration (such as the Next Generation Safeguards Initiative) propose to advance the use of PM by demonstrating quantitatively the added value of PM in conjunction with NMA.

This paper reviews traditional PM roles and then illustrates possible new PM roles using two diversion scenarios. In the two diversion scenarios, as in NMA, the safeguards system figure of merit is the alarm probability for a specified diversion, which we denote as Prob(alarm|diversion). In NMA, a diversion is characterized by the amount of special nuclear material (SNM) loss over specified balance periods. In PM, diversion will still be characterized by loss amount and balance periods, but also by ***how*** the diversion occurs so that signatures and observables are included among the *scores* used to monitor the facility. Example scores include MBs and residuals from PM as described in Section 5.

The fact that PM instrumentation can be chosen or optimized for selected diversion scenarios can be regarded as a curse or blessing. It is a curse because considerable modeling and knowledge are required to characterize observables from each modeled scenario and because not all scenarios can be anticipated. It is a blessing because PM can be very effective against specified diversions, and because PM together with NMA can lead to increased safeguards effectiveness as measured by Prob(alarm|diversion) as we show by example.

2. Background

This section provides additional but brief background on NMA and PM. Traditionally, safeguards effectiveness is quantified using only NMA but it is recognized that PM and containment and surveillance (C/S) increase overall safeguards effectiveness.

2.1 Nuclear Material Accounting (NMA)

Typically, many measurements are combined to estimate the terms T_{in}, I_{begin}, T_{out}, and I_{end} in the MB; therefore, the central limit effect and years of experience suggests that MBs in most facilities will be approximately normally distributed with mean equal to the true SNM loss L and standard deviation σ_{MB}, which is expressed as MB ~ N(L, σ_{MB}).[1]

The magnitude of σ_{MB} determines what SNM loss L leads to high detection probability (DP). For example, following IAEA convention, suppose the facility tests for SNM loss only, not for SNM gain, and assume that MB ~ N(L, σ_{MB}) is an adequate model. Then, if a false alarm probability of $\alpha = 0.05$ is desired, the alarm threshold is 1.65 σ_{MB}. Alternatively, if the facility tests for loss or gain, then the alarm threshold for $\alpha = 0.05$ is 2 σ_{MB}. In the case of testing for loss only, it then follows that the loss detection probability 1- $\beta = 0.95$ for $L = 3.3\ \sigma_{MB}$ and $1 - \beta > 0.95$ if $L > 3.3\ \sigma_{MB}$, where β is the fail-to-detect (false negative) probability. The factor 3.3 arises from symmetry of the Gaussian, requiring $\alpha = \beta = 0.05$, and the fact that 1.65=3.3/2 is the 0.95 quantile of the N(0,1) distribution.

For facilities under IAEA safeguards, one goal is for the loss DP 1-β to be at least 0.95 if $L\$1$ SQ (significant quantity, which is 8 kg for Pu), which is accomplished if and only if σ_{MB}#SQ/3.3. If σ_{MB} > SQ/3.3, this can be mitigated either by reducing measurement errors to achieve σ_{MB} #SQ/3.3 (if feasible), and/or by requiring enhanced material containment and surveillance (C/S) such as smart camera and remote radiation detection. However, the increased C/S effort level is challenging to negotiate, and the resulting C/S effectiveness is difficult to quantify.[2]

Large throughput bulk-handling facilities will try to make σ_{MB} as small as reasonably possible, and often try to keep σ_{MB} small as a percent of throughput (perhaps $\sigma_{MB} < 1$ percent of throughput depending on facility type[3]), but cannot achieve σ_{MB} #SQ/3.3. For example, with a measurement error relative standard deviation of 0.3 percent of throughput (a typical goal for a large reprocessing facility), and the IAEA's DP goals ($\alpha = \beta = 0.05$) for an 8,000 kg annual Pu throughput (1 percent of an 800 metric ton heavy metal throughput), the diversion would have to be 3.3 x 0.003 *x* 8000 kg = 92 kg or larger.[1,4] This is much larger than one SQ, so protracted diversion of 1 SQ over one year is not likely to be detected.

In such cases, one reasonable approach is to evaluate the cost of reducing σ_{MB} as a function of measurement type(s) and translate the result to a relation between σ_{MB} and cost.

One would then choose the cost where the relationship flattens (diminishing returns) and accept the resulting σ_{MB}. It is generally agreed that the resulting σ_{MB} will be too large in large facilities to meet the IAEA goal for slow (*protracted*) diversion occurring over one year for example, but there is reasonable hope that the goal can be met over perhaps 10 days or less.[1,4] Therefore, more frequent balance closures (using PM to assist NMA by estimating SNM holdup) perhaps every ten to fifteen days are being used at the Rokkasho reprocessing plant (RRP).

For facilities as large as RRP, PM is an added measure that can address some of the limitations of NMA, as described next.

2.2 Process Monitoring (PM)

PM is an established safeguards measure that complements NMA. The scope of quantitative nuclear safeguards is broadening from NMA to include PM, which has both C/S[6,7] and NMA features. Although PM has been used as a component of safeguards, as with C/S, there have been very few attempts to quantify its benefits. Clearly the benefits of PM depend on its roles in the overall safeguards system. In a broad sense, here are three possible roles for PM:

a) NMA remains objective/quantitative basis for DPs and PM is used for example to resolve alarms, support measurement error models, and assist with in-process inventory estimation.
b) PM moves into the driver's seat to trigger physical inventory taking for NMA. Several facilities are experimenting with this option; however, the benefits of this approach have not been quantified.
c) PM and NMA are on "equal footing," which will be the main emphasis of this paper, and several challenges arise with this option (see Section 6 for further discussion).

Facilities that cannot meet the IAEA DP goal will have negotiated levels of additional measures including PM and C/S measures, such as smart cameras and tamper indicating devices beyond the usual requirements.[8]

PM data can be dedicated for safeguards use but can also include process control measurements such as those used by the operator to control the chemical processes.[9] Example process control measurements in an aqueous reprocessing plant include mass and density measurements in tanks, inline flow meters, concentration measurement of nonnuclear material reagents, and process temperatures. As a rough comparison to NMA, PM data is often collected frequently (multiple times per hour) while MBs are computed less frequently (perhaps every ten days at large aqueous reprocessing plants). And, PM data often tracks bulk attributes such as mass rather than SNM mass.

PM goals include support to NMA, but also PM has a *front-line* role to detect changes that could indicate facility misuse and to provide continuity of knowledge to support confirmation that the facility is operating as declared. The basic concept is that facility misuse will generate observables that PM + NMA has the potential to detect better than NMA alone. For example, altered material flow rates[5,10] could imply an attempt to misdirect SNM, so inspector access to operator flow rate data can provide a quantifiable benefit.

As an example of PM to be considered in more detail in Sections 4 and 5, solution monitoring (SM) is a type of PM in which masses and volumes are estimated from frequent in-process measurements. If each tank is regarded as a sub-MBA (material balance area), then transfers between tanks can be identified, segments of which can then be compared to generate transfer differences (TDs). A safeguards concern might then be raised if either these TDs or deviations in mass or volume data during *wait* modes become significant.[10-15] Average mass and volume TDs should be zero (perhaps following a bias adjustment) to within a historical limit that is a multiple of the standard deviation of the mass or volume TD, as should deviations during wait modes. A residual (residual = measured – predicted) is generated each time a mode (transfer or wait) is completed by any tank. Such residuals can be analyzed over time and over tanks. Analogously, in NMA one can analyze MBs for trends over time. As an aside, another approach to SM that relies on having consistent tank cycles defines a template signature for each tank and monitors each cycle for agreement with the historical template.[16] This alternate SM approach also generates residuals or scores.

The benefits of PM will obviously depend on how PM data are used. For example, four possible tasks for SM as a type of PM in support of NMA are to:

- Help understand facility status at the time of interim inventory for NMA
- Assess the adequacy of measurement error models such as those used to quantify the uncertainty in solution volume measurements for NMA. This can be done by evaluating the volume shipped by an upstream tank to the volume received by the downstream tank. [11,12,17]
- Provide a "by-difference" estimate (and associated uncertainty) based on measured inputs and outputs of material holdup in process equipment that is not directly measureable but is bracketed by measurement points.[18]
- Provide an inferred or estimated "book value" for waste or other low-Pu-mass streams that allows tighter control limits than are possible with NMA alone. Such a "book value" requires SM to be used in conjunction with models of unit operations.

The two diversion scenarios in Section 4 focus on tasks 3 and 4, putting PM and NMA on "equal footing" as in role c) for PM.

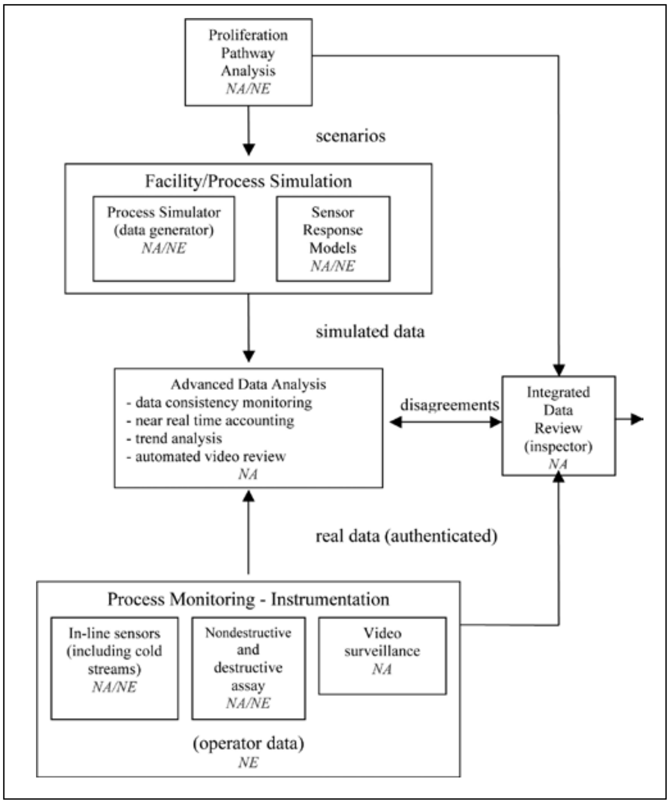
3. Quantifying Safeguards Effectiveness

At least two obstacles have historically prevented developing an overall safeguards evaluation methodology. First, there is general agreement that C/S adds value, but there is no consensus regarding how to take quantitative credit (for example, through improved loss DPs) for C/S in the same manner that improved accountancy measurements are given credit (through reduction in σ_{MB}). Second, there is no consensus regarding the utility of enumerating and characterizing the most likely diversion routes and scenarios. Therefore, some assume that because no system can detect all types of diversion,[19] there will be arbitrary decisions made regarding what diversion scenarios the system should detect and therefore what C/S measures will be used. In effect, it is assumed by some that the system design should be decided by arbitrary but reasonable decisions made by the safeguards experts responsible for a given facility.

Alternatively, using NMA, PM, and perhaps C/S in a combined manner, makes it possible via modeling and simulation to estimate system DPs for a few key specified diversion scenarios and possibly also some unspecified scenarios. Unspecified scenarios will have lower DP, but unspecified scenarios will cause measurable effects on normal plant data. Therefore, outlier detection schemes that detect any shift in normal plant operation can be devised to have at least reasonably high DP to detect atypical data associated with unspecified diversion scenarios.

Current efforts using modeling and simulation are therefore underway to quantify the benefits of NMA and PM in terms of system loss DPs.[4,5,11,12,17,20,21] Additionally, experimental efforts for online monitoring of Pu and other elements relevant for PM are underway.[22] Also, effective PM requires facility models such as described in the two examples in Section 4. Such models provide valuable insight regarding what diversion scenarios are plausible, so decisions regarding safeguards subsystems need not be as subjective as Lyman[19] suggests. Preliminary and mostly conceptual efforts are also underway to quantify the combination of C/S (including physical protection) with NMA and PM.[23] Our focus here is on the combination of NMA and PM.

Figure 1. Process monitoring tasks. NA and NE are the nuclear non-proliferation and nuclear energy agencies



Designing an effective safeguards system that is "good enough" without being too costly is a practical goal with significant challenges. A similar goal is to be able to compare and rank candidate safeguards approaches/systems so that the cost/benefit of purported improvements can be evaluated. These two goals are driving safeguards professionals to consider how modeling and simulation can be used to quantify the benefit of NMA, C/S, and PM, which are the three key data-driven safeguards systems.

In the context of quantifying safeguards effectiveness when NMA and PM are used on equal footing, **the overall goals are to:**

- Quantify the possible benefits of PM both in support of NMA and as a frontline loss detection tool. PM is compelling as a frontline loss detection tool for large scale plants having large absolute uncertainty in NMA, and also compelling from a safeguards cost perspective for any sized plant because much PM data is already being collected for process control reasons, and so can be available for safeguards at very low cost.
- Make steps toward a virtual facility simulation capability in order to model (part of the *curse* of PM mentioned in the Introduction) and assess diversions routes; to evaluate associated misuse signatures such as tank cycle times, acid flow rates or concentrations and temperatures, and to evaluate potential sensor responses.

4. Two Diversion Scenarios

Here we present two scenarios in which supplementing NMA with PM will increase DPs.

The vision for PM requires that we simulate diversion scenarios to quantitatively evaluate PM options (see Figure 1). We first describe a diversion scenario in the head end of a generic aqueous reprocessing facility and then a scenario in the separations area. Both scenarios are plausible and difficult for NMA to detect, with a daily Pu throughput of 53.4 kg.

4.1 Diversion Scenario 1

Misdirect excess Pu to the leached hulls (a waste stream) following incomplete dissolution in the dissolver. Note added from a reviewer: Such misdirection of Pu to the hulls is a diversion from the monitored head-end; however, if the hulls remain under safeguards, there might still be detection by some means not considered here.

NMA in the head-end of the plant consists of shipper-receiver differences between reactor calculations of the Pu in the spent fuel and the measured Pu in the input accountability tank (IAT). The hulls monitor can be calibrated under certain assumptions so that Pu in the hulls waste stream can be included with the Pu in the IAT. The estimate *output* Pu includes hulls waste and IAT product that together are compared to the shipper's value based on reactor burnup calculations. That is, the shipper-receiver difference is a type of NMA that compares input burnup calculations to the sum of output hulls indirect Pu measurements and IAT direct Pu measurements.

The dissolver can be run for example at a low temperature for a less-than-nominal cycle time to send excess Pu to the hulls.[5] Reactor burnup and/or cooling time can be misdeclared to modify the book Pu value anticipated in the hulls. Regarding a book Pu value for each hull batch, some facilities (Tokai reprocessing plant, TRP) have inconsistent Pu content in the hulls because of inconsistent cladding cut lengths and inconsistent procedures for hull rinsing. Rokkasho (RRP) has more consistent Pu content in the hulls, and is expected to have a more consistent ratio of Cm to Pu (the neutron hull monitor mainly measures neutrons from Cm and assumes a constant Pu/Cm ratio in the head end). This leads to two cases:

- **Case 1:** each hull batch has a consistent (and small, such as 0.1 percent, see below) Pu content and Pu/Cm ratio so the neutron hull counter gives a relatively consistent reading, resulting in a book value for each hull batch.
- **Case 2:** hull batches have an inconsistent Pu content and/or Pu/Cm ratio so there is no effective book value for hull batches.

Case 1 is safeguards friendly, meaning that inspectors will have relatively high confidence in their assessments. And, because a neutron hull counter is a type of PM, this is an example where PM is already used to support NMA effectively. In fact, the hulls monitoring helps track material in the head end to reduce the chance of another THORP-facility-type (thermal oxide reprocessing facility in England) incident in which large amounts of Pu were leaking and eventually detected by shipper-receiver difference evaluation.

Case 2 is not safeguards friendly, because hull batches cannot be monitored except as a small output stream to be combined with the IAT measurement, thus reducing loss detection capability of the hull monitor because of the large IAT absolute measurement uncertainty.

Pu Throughput for Diversion Scenario 1:
53.464 kg in three dissolver batches per day which implies 17.8 kg Pu per batch. The nominal Pu to hulls: 0.1 percent, so 17.8 g Pu per hull batch.

The Diversion: 0.527 percent Pu by weight undissolved (sent to hulls) instead of the nominal 0.1 percent Pu, which directs an *excess* of approximately 0.43 percent Pu to the hulls. In order to divert an SQ of 8 kg of Pu, this requires approximately 105 *bad* hull batches because 105 batches x 17.8 kg/batch x 0.0043 < 8kg over thirty-five or more days (not necessarily consecutive days) because there are only 3 dissolver batches per day.

The standard calculation in Section 2.1 assuming the relative measurement error in the smallest real difference (SRD) is 3 percent of the throughput, with a 95 percent DP goal at 5 percent false alarm probability requires $s_{SRD} < 8/3.3 = 2.42$, but $s_{SRD} > 2.42$ after approximately 1.5 days. Most of the "measurement error" in the 3 percent error budget is due to reactor burnup calculations (Garcia et al.[21]). The rest of the 3 percent relative error budget is due to the hulls measurement and the input accountability tank measurement.

Remarks for Diversion Scenario 1:
R.1) Because of the relatively large uncertainty in the reactor calculations, this scenario is difficult for NMA alone (shipper-receiver differencing) either for Pu or U tracking. The assume relative error for U is also 3 percent, as for Pu, which is our focus. However, Case 1 can be safeguarded effectively because there is a nominal or book value for each hull batch. So, PM in the form of a hull monitor provides effective frontline detection capability.

R.2) Case 2 would pose a difficult safeguards challenge. However, numerical results are available [5] assuming much shorter dissolution time and/or lower temperatures in order to send an excess of 8 kg of Pu to the hull more than 105 bad batches. The dissolver model can provide a model-based "book value" for the hull Pu content and associated neutron hull monitor counts.

R.3) Misdeclaration of the spent fuel properties is not currently exploited by the adversary as part of the Case 2 scenario. Suppose the operator did misdeclare fuel properties to spoof the model-based book value concept in remark R2. That is, excess Pu could be sent to hulls batches without inspector detection if the hulls monitor measurement agreed with the deceptive book value arising from falsely declared spent fuel properties such as fuel burnup. However, if burnup of one or more dissolver batches is misdeclared, then the multi-isotope PM[24,25] can play a role, because early studies suggest that the multi-isotope process monitor can distinguish among reactor burnups, cooling time, and temperatures, providing a possible check on operator declarations. This is a role for PM that is not yet fully developed because data falsification is included in the misuse or diversion scenario (see Section 6).

R.4) SM could help verify the declared dissolution time in the dissolver by confirming the cycle time in the dissolver. This requires careful attention to "solution monitoring scoring systems," [26] because many tank cycle features would be monitored frequently. However, we anticipate essentially zero mistake rate in recognizing for example the difference between a dissolver dissolution time of 765 minutes (nominal) and 561 minutes (which could send an extra 0.4 percent to the hulls if there were no processing change except for the shorter dissolution time).

R.5) Under Case 1, this scenario is probably detectable because of the large shift from 0.1 percent to 0.527 percent Pu in the hulls. However, hull monitoring must be considered to be one statistical test among many in the head end, so we must adjust the alarm limits for multiple tests. Under Case 2, this scenario relies on NMA and so will not be detected.[5,21]

4.2 Diversion Scenario 2

Lower than nominal nitric acid concentration is used in the aqueous feed to solvent extraction, causing excess Pu to go to the waste tank.

NMA is vulnerable in the tanks that feed or receive from the separations cycles because these tanks have continuous modes, making real-time monitoring difficult unless all pipe feeds can be monitored. However, current models[27] suggest that relatively little Pu can be misdirected to the auxiliary waste tank in the first separations area under the assumed conditions. Other conditions are being investigated as the separations model progresses. Nevertheless, some Pu can certainly be misdirected to the auxiliary waste tank, so if multiple solvent extraction areas (which purify the Pu and/or U streams) are involved, Diversion Scenario 2 has the potential to accumulate 8 kg of Pu over a time frame to be evaluated in future work. Therefore, model-based book values for Pu entering waste tanks (analogous to book values for Pu in the hulls in Diversion Scenario 1) could be the basis for an effective PM role.

One contribution of this modeling effort is related to goal 2 in section 3: to "assess diversion routes." Certainly dissolver and solvent extraction models are valuable for understanding the boundaries within which an operator must lie for safe operation, and for quantifying the process changes required to misdirect specified amounts of Pu.

Remarks specific to Diversion Scenario 2:
R.6) The multi-isotope process monitor under development can detect process shifts, such as shifting nitric acid concentration which could indicate direction of excess Pu to the waste stream. There is also current work on UV-Vis and other hyperspectral methods to monitor several constituents (hot or cold stream) on-line.[22,24,25] Some of these methods have the potential to estimate in-line Pu concentration which would directly support NMA. Other methods estimate constituents whose concentrations can, in conjunction with an appropriate process model, provide a separations cycle monitoring scheme that is analogous to monitoring the dissolver in Diversion Scenario 1 for indication of excess Pu left with the hulls.

Remarks for Diversion Scenarios 1 and 2:
R.7) SM data evaluation systems need to further investigate the impact of continuous mode tanks. For NMA, the operator samples the B/B (batch receipt, batch ship) buffer tank upstream of the B/C (batch receipt, continuous ship) feed tank and uses mixing rules to estimate Pu in the B/C tank. The operator samples the C/B (continuous receipt, batch ship) receipt tank downstream of each separation cycle.

R.8) Nearly all SM evaluations have essentially focused on operator loss DP. However, RRP authenticates approximately twelve of eighty tanks, with "type 1 tanks" having essentially independent IAEA measurements and "type 2 tanks" relying solely on operator measurements.[7,28,29] In type 1 tanks, the inspector is present during tank calibration of the dip tube system, and the inspector owns and controls pressure sensors connected to the dip tubes. Suppose in a 3-tank system Tank 1 ships to Tank 2 which ships to Tank 3. And, suppose Tanks 1 and 3 are type 1 and Tank 2 is a type 2 tank. A key benefit of SM is the ability to check tank-to-tank transfers on a per-batch basis. Provided Tank 2 simply passes solution on to Tank 3, there is some ability to authenticate Tank 1 to Tank 3 comparisons. In effect, there is a book value for the receipt by Tank 3.[29]

5. Options to Combine PM and NMA Data on Equal Footing

One way to combine PM and NMA on equal statistical footing is to let both systems report residuals (*scores*) as they arrive. For SM, such scores arrive at the end of each tank-to-tank transfer in a scheme that regards each tank as a sub-MBA[11,12,13] and NMA is performed, for example, every ten days. Figures 2 and 3 provide a qualitative notion of such a system. Efforts to quantify the DP are underway and more detail is given below.

For a scenario such as Diversion Scenario 2, a 7-tank MBA includes batch and continuous mode tanks, a separations area between Tanks 2 (Feed) and 3 (Receipt), and the notion of predicted or book values for the waste stream exiting the separations area and for holdup in the separations area.

The next two subsections give more detail about two options to combine PM and NMA data.

5.2 Pattern Recognition Approach

Pattern recognition is one option to evaluate PM and NMA data on equal statistical footing. The basic goal in pattern recognition using vector-valued observations such as time series of NMA and PM scores is to recognize off-normal data.[30,31,32]

Remark:
R.9) Pu mass measurements in waste streams are a component of the material balance, and these same measurements of waste stream Pu mass can be compared to the model-based book value, resulting in two correlated scores, one score being the MB and another score being the comparison between book and measured waste stream Pu mass.

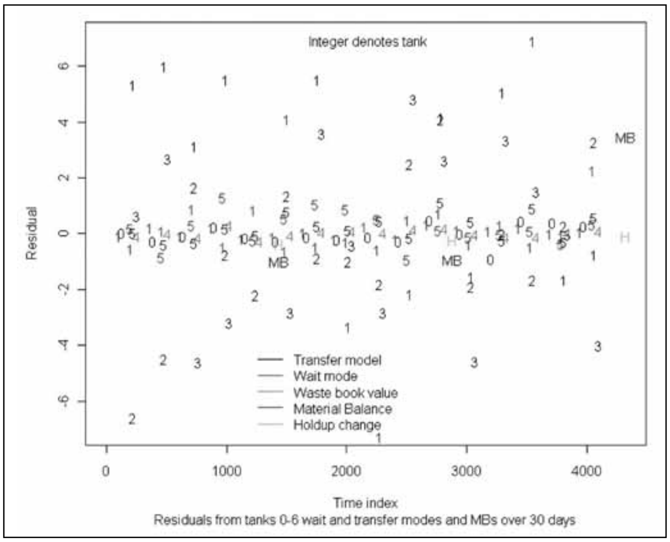
Additional scores beyond those mentioned in remark R.9 arise in the approach where each tank is a sub-MBA and is monitored for *M* and/or *V* loss during all wait and *transfer* modes[11]. Doing so requires event marking which requires some care. Current implementations[33] provide a "point editor" to the inspector to modify initial estimates of change point marks.

This 7-tank MBA includes batch receipt and batch ship tanks (B/B mode) plus batch receipt and continuous ship tanks (B/C) tanks plus continuous receipt and batch ship tanks (C/B) and holdup and waste. Both holdup and waste have "book values" provided by a model of the pulsed column operation. Efforts are underway to resurrect and improve pulsed column models [5,34] but for our purposes here using simulated data with random and systematic measurement errors (but no process variation) as in Burr and Howell[11] or Cipiti,[4] the pulsed column model is assumed to provide a total relative error standard deviation of 10 percent. We have quoted "book value" here because NMA sometimes uses the term book inventory to mean $T_{in} + I_{begin} - T_{out}$ which is compared to physical inventory. The book value therefore comes from a model either in the PM context with waste streams or in the NMA context with MB accounting. The term process variation is a generic term that captures sources of variation other than pure measurement error effects, such as inconsistent operation of the pulsed columns (i.e., the solvent extractors).

Figure 2 plots simulated scores from monitoring each tank's wait modes and all tank-to-tank transfers from the three MBs over 30 days (one MB every ten days), and from comparing three SM-based measurement to each of the three book values for holdup and for waste.

How should we evaluate a multivariate time series such as plotted in Figure 2 for loss of Pu mass? To complicate matters,

Figure 2. Residuals or scores from NMA and PM for the seven tanks (tanks 0 to 6)

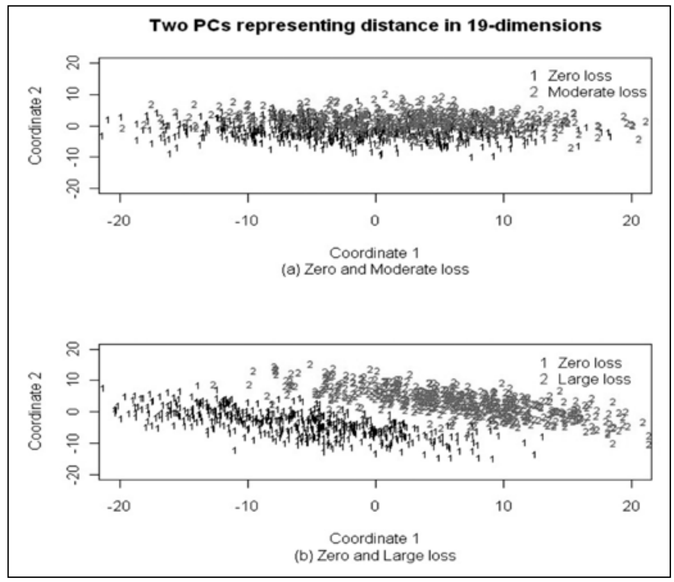


PM data and NMA data are not independent in general. For example, the same dip tubes that measure volume in SM data for each tank are used for the volume measurement for NMA. Also, the same waste measurement that is compared to a book value (recall remark R.2) is also used as an *output* in the MB for NMA. Other examples of complicating issues are shown in Burr and Hamada[31] and in related work to be published.

Combining NMA and SM scores such as those shown in Figure 2 into an overall system having small false alarm probability is ongoing work involving custom pattern recognition methods. Burr and Hamada[31] provide preliminary assessment of options to combine such multivariate time series using a simple distance-based pattern recognition method applied to multiple sequential test statistics. Figure 3 qualitatively illustrates one such option for developing an alarm rule based on pattern recognition applied to multiple time series.

Figure 3 uses principal coordinates to display scores from nineteen separate sequential tests (Page's test[35]) applied to the nineteen scores from NMA and SM over thirty days spanning three ten-day NMA balance periods. The nineteen scores include ten wait and transfer mode scores, three waste measurements compared to the waste book value, three holdup estimates based on SM data compared to the corresponding holdup measurement, and three MBs. Burr and Hamada[31] show that the combined NMA and SM data using the Mahalanobis distance from the zero-mean (zero loss) case as the alarm criterion (a simple pattern recognition option) has moderate DP for a moderate loss and large DP for a large loss. Because Page's sequential test checks for temporal trends over the thirty days, Figure 3 is not intended as a check for trends, but is intended only to evaluate how detectable a moderate or a large loss is with one particular pattern recognition option.

Figure 3. Qualitative assessment of the ability to detect moderate or large loss using NMA and PM data from Figure 2. Two principal coordinates (similar to principal components) are used to show distances between nineteen-component realizations. Because Page's sequential test checks for temporal trends over the 30 days, Figure 3 is not intended as a check for trends, but is intended only to evaluate how detectable a moderate or a large loss is with one particular pattern recognition option.



Options involving sequential statistical testing applied to NMA with frequent balance closure were first investigated for safeguards in the 1970s and 1980s. Speed and Culpin[2] summarize that early work by several safeguards organizations around the world, including the IAEA. Although various sequential statistical tests such as Page's test are appropriate for frequent MBs in NMA (such as closing balances every ten days), Avenhaus and Jaech[36] showed that more frequent balance closure in NMA does not increase loss DP for wide-spread (*protracted*) diversion over time. In fact, less frequent balance closure has higher DP if the loss vector describing the loss at each balance period is proportional to the sum of the rows of the MB covariance matrix Σ (which has σ_{MB} along the diagonal and covariances between MBs at different balance periods on the off-diagonal). A similar conclusion holds for wide-spread diversion over time and space (multiple tanks in our context).

The PM and NMA scores are a multivariate time series. If the multivariate scores are assumed Gaussian, then a similar calculation to that in Avenhaus and Jaech[36] shows that less frequent monitoring has higher DP for some loss scenarios that are protracted over time and spread over multiple tanks. *Therefore, PM combined with NMA is not a panacea. However, our models predict that PM combined with NMA does have very high DP for diversion scenarios 1 and 2.* In addition, Burr and Hamada[31] illustrated that PM scores are not necessarily Gaussian distributed, so additional work is required to estimate the effects of non-Gaussian scores and develop system-centric (Section 5.2) and/or pattern recognition methods that are effective for non-Gaussian scores. Also, frequent multivariate scores (whether approximately Gaussian or not) as we have assumed are available from PM data will have much higher DP against most loss scenarios, particularly abrupt loss. Analogously, frequent balance closures in NMA performs better in an overall sense than infrequent scores from NMA alone, simply because frequent balance closures leads to much higher DP for abrupt diversion, and only slightly lower DP for protracted diversion. And, alarm rules involving pattern recognition can be made to have almost the same DP against protracted loss as for example an annual NMA-based balance closure. To summarize, it is anticipated that while not a panacea, frequent multivariate scores from NMA and PM will perform better in an overall sense than infrequent scores from NMA alone or from PM and NMA.

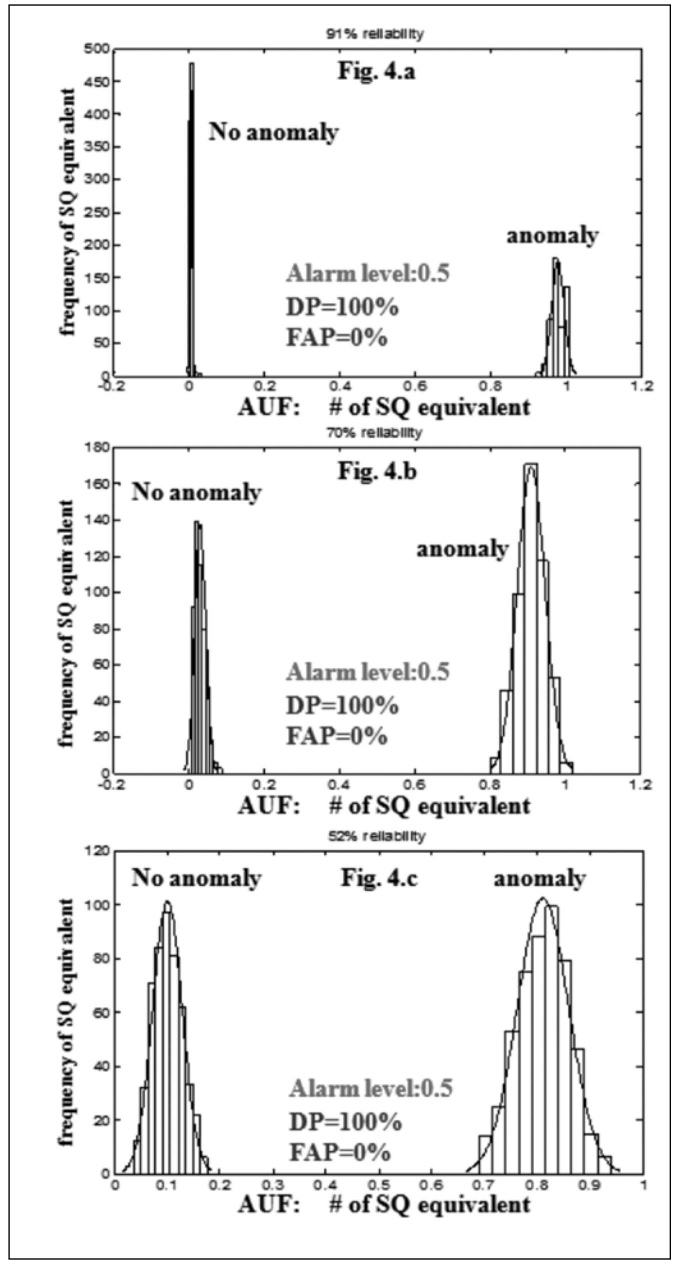
5.2 System-centric Approach

Garcia et al.[21] describe another possible way to combine multiple subsystems that relies on "anomalies unaccounted for" (AUF). The approach currently assumes that each subsystem is independent and uses a very specific alarm rule involving various sensors reporting either abnormal or normal status. It allows for the partial observation case, in which missing sensor information is inferred from other sensors. In addition, each sensor is characterized by a reliability defined by its false-pass and false-fail rates. It uses a discrete event model of operations and allows for inference of missing sensor values. This is an example of an overall system, and one could add NMA as a subsystem and treat NMA on the same footing, but not independent of SM.

Garcia et al.[21] report high DPs for Diversion Scenario 1 in the dissolver that NMA alone can detect only with very low DP. This approach works with categorical data from each sensor, such as L (low), M (medium), and H (high), allowing for tuned time-delays from some sensors to model a temporal trend. Figure 4 (a-c) illustrates high DP results for Diversion Scenario 1 for three values of sensor reliability. Sensor reliability determines, for example, a sensor's probability of correct classification into the L, M, or H categories. An example AUF would then be an H reading on a sensor that should read M.

Although the estimated DPs are very high, and there is clear separation between the non-anomalous and anomalous data (unlike in Figure 3 where group separation is not so dramatic), real plants are quasi-continuous, the approach is tuned to this particular scenario, and subsystems are currently assumed to operate independently (not true for SM and NMA for example). Therefore, additional development is required to modify the current system-centric approach applied to Diversion Scenario 1 using the dissolver model from Bakel et al.[5]

Figure 4. Systems-centric approach from Garcia et al.[21] AUF is "anomalies unaccounted for"



6. Discussion

Process monitoring (PM) is an established safeguards measure that complements NMA. Recall the three possible roles for PM described in section 2.1, and that this paper's focus is role (c), in which PM and NMA are on "equal footing." For role (c), we now describe six technical challenges in more detail.

T.1) The false alarm probability must remain low. One concern with including PM data with NMA data is that the false alarm probability will need to remain low while allowing for atypical but innocent sources of process variation such as pump carry-over (which leads to temporary apparent solution gains and losses during tank transfers) and solution evaporation. Real data allows us to add realism to simulated data so that alarm thresholds estimated from simulated data are similar to those estimated from real training data. Several real data sets are available including SM data from Savannah River National Laboratory, Tokai-mura, Idaho Chemical Reprocessing Plant, and Barnwell facilities. Burr and Hamada[31] describe first steps toward assessing the impact for example of non-Gaussian data on estimated alarm probabilities in SM scores. The required degree of model fidelity for adequate DP estimation is difficult to gauge, but should be addressed.

T.2) Because data tampering can mask diversion, data authentication is a concern, particularly for international safeguards, but also for domestic safeguards in any country. One approach to reduce the need for independent inspector equipment is related to type 1 tanks as described in remark R.8.[28,29] Strategies to authenticate operator data are briefly described in Section 7.

T.3) There is an ongoing need to monitor sensor health, and sensor monitoring is partially included in Python software (Bevan et al.[20]) in which a sensor fault is always a possible explanation for an apparent anomaly. A hybrid approach is to use Crosier's bivariate cusum[34] to flag unusual events (anomalies), and the reasoning module in Bevan et al.[20] to resolve/classify anomalies. Also, Hines et al.[37] applied "phase 1 control chart" learning strategies to learn normal behavior and monitor for instrument drift. Additional research is needed to filter out false alarms caused by instrument drift and/or temporary anomalies.

T.4) Scores from NMA and SM are not independent. For example, PM can support NMA by providing a "by difference" basis to estimate change in separations area holdup. This approach works reasonably well for a given period to estimate the change in holdup, although measurement errors accumulate over time, just as in NMA. It does not typically work as well to estimate actual holdup, partly because holdup estimation[34] is more difficult than holdup-change estimation. In either case, if PM and NMA scores are combined on equal footing, correlations arise among scores associated with holdup or holdup-change estimation.

T.5) Although it is acceptable to tune to a few loss scenarios, a catch-all anomaly detection option is needed for scores that are unlike anything seen in phase I monitoring. Phase I monitoring is the *training* phase for a combined NMA/PM system where alarm rules are developed (pattern recognition methods are *trained*) on data that is assumed to be free of diversions. The trained methods are then tested on new (*testing*) data. Most current work related to training a combined NMA/PM system has been applied to simulated training data. There are ongoing efforts to improve the simulation fidelity so that simulated data has adequate quality to mimic key features in real NMA/PM data.

T.6) Using the figure of merit P(alarm|diversion scenario), some scenarios must be modeled, which requires considerable R&D, particularly for scenarios that include the possibility of the operator falsifying data to conceal diversion. For estimating P(alarm|diversion scenario), modeling, simulation, and analysis are among the high priority tasks in safeguards initiatives such as the Next Generation Safeguards Initiative.

In addition to these technical challenges, there are practical considerations involving: (7) the requirement for greater access to the plant operator's process control data, (8) the need to leverage and/or develop new process control instrumentation for PM use, and (9) the need to reduce inspector time required to evaluate PM data, particularly because enhanced PM for the future will likely include additional operator data.

For consideration 7, there can be concerns regarding proprietary information, so information barriers in addition to existing privacy protections might be needed. Information barriers can include data transformations that avoid revealing sensitive data. For 8, there is no requirement to use only existing operator data, and new types of control data are continually being developed. For 9, the inspector must not be frequently responding to alerts to evaluate innocent but atypical operating data. There are legitimate concerns about false alarm rates if the data spigots are in high volume. We anticipate the need for smart software tools such as in Bevan et al.[20] that analyze and archive all relevant PM and NMA data, but only very infrequently alert the inspector to possible data anomalies.

7. Data Authentication

The IAEA takes significant measures to ensure that data from its systems are authentic. IAEA safeguards equipment is typically installed in sealed tamper indicating enclosures, and unauthenticated or unencrypted signals cables are enclosed in tamper indicating conduit. Data transfers from the equipment are sent over a virtual private network (VPN) or downloaded by inspectors at the instrument.

Instrumenting all tanks at large scale facilities such as reprocessing plants with traditional authenticated safeguards instrumentation systems for NMA can be cost prohibitive, so there is a need for PM using operator measurements as an additional measure to NMA. However, when using PM equipment that is owned by the facility operator, the IAEA does not control the equipment; the operator manages the calibration, operation, data collection, and data dissemination from the PM equipment. This makes the application of traditional equipment authentication difficult or impossible. However, there are measures that can be employed to increase IAEA confidence in data from PM equipment not under its sole control.

Trust hierarchies can provide assurances to increase IAEA trust in operator PM data.[28] The key idea is to increase trust in an operator's PM data by testing or comparing the operator's data with data from IAEA owned and controlled systems that are trusted. At a large facility like RRP, IAEA-owned systems, as with the instrumentation in type 1 tanks, monitor key points in the plant. Utilizing the trust hierarchy concept, the IAEA data can be compared and correlated to operator-owned process monitoring data from type 2 tanks, and other related points in the plant, to establish the trust relationship and increase IAEA confidence in the data from the operator owned PM systems.

8. Summary

Quantifiable benefits of PM have been described for aqueous reprocessing plants. PM is currently used at other facility types, and while its benefits and roles for other facility types are continually being evaluated, to our knowledge this is the first article to explicitly consider PM on "equal footing" with nuclear material accounting (NMA).

Regardless of whether PM is ever actually placed on equal footing with NMA, we anticipate that PM will continue to support NMA in various ways such as roles (a) and (b) for PM from Section 2.2. For example, solution monitoring as an example of PM provides data and model-based indirect measurement of in-process inventory and/or holdup, which is required for frequent balance closure.[6,7,34]

Compared to NMA, in some ways it is more difficult to make effective use of PM data because modelling and simulation are required. However, the technical effort to effectively use PM data is within the capability of modern facilities, particularly in the context of increased attention to safety considerations that also require detailed understanding of normal plant operations.

Although we strongly endorse PM to improve safeguards, we recognize that significant technical challenges for use of PM data include those listed in the Discussion Section to: maintain a low false alarm probability, authenticate PM and NMA data, monitor sensor health, deal with non-independent and non-Gaussian "scores," detect any off-normal operation while also being tuned to a few specific misuse scenarios that are well understood via modeling. Assuming access to training data that does not include any material diversion, PM and NMA can also be combined to detect unspecified misuse by using outlier detection methods that are under development. Practical considerations include the need for greater access to operator PM data and the need to reduce inspector time needed to analyze PM data.

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Report on the INMM Workshop on Preparing for Nuclear Arms Reductions to Address Technical Transparency and Verification Challenges

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Abstract
In May 2011, a workshop was held to develop broader awareness of the technical and operational challenges that could be used to enhance effective transparency and/or verification in the medium to long term. Building confidence in a broader multi-lateral engagement scenario adds even greater challenges than the traditional bilateral approaches. The multi-disciplinary group that attended included decision-makers needing to understand present and possible future technical capabilities, and the technical community needing clearer definition of possible requirements and operational constraints. In additional to traditional presentations, the group conducted an exercise to stimulate new perspectives on verification requirements for a scenario based on nuclear arms reductions at very low numbers of nuclear weapons. This presentation will summarize the outcome of the workshop and anticipated follow-on efforts.

Introduction
In Prague on April 5, 2009, President Barack Obama "… state[d] clearly and with conviction America's commitment to seek the peace and security of a world without nuclear weapons. I'm not naive. This goal will not be reached quickly –- perhaps not in my lifetime. It will take patience and persistence." As governments grapple with the defense and foreign policy decisions that must be taken to work towards the long-term goal of nuclear arms reductions, professional societies, such as the Institute of Nuclear Materials Management (INMM), have initiated forums to bring together technology developers, defense/foreign policy experts and students to develop and explore ways to achieve this challenging objective.

In close cooperation with the James Martin Center for Nonproliferation Studies (CNS) at the Monterey Institute of International Studies (MIIS), the Lawrence Livermore National Laboratory, and the INMM's Nonproliferation and Arms Control Technical Division a workshop was organized to:

- Consider government perspectives and results of a recent National Academy of Sciences (NAS)/United States Institute of Peace (USIP) Symposium,
- Focus on technical challenges related to achieving greater transparency and verification of compliance with future commitments, and
- Conduct an exercise to challenge participants to think about what would be required to move toward a world with *zero* nuclear weapons.

Overview of Presentations
During the first session of the workshop, U.S. and UK representatives spoke about their governments' views on exploring options for future nuclear weapons stockpile reductions. They stressed the important capability that technology provides to monitor and verify commitments related to nuclear testing, accountability of warhead numbers/locations, possible future weapons dismantlement programs, and the disposition of fissile materials for use in nuclear weapons. Existing and evolving technologies can help governments move towards these desired policy objectives so a robust dialogue between the technical and policy communities is essential. It was also recognized that engagement must extend beyond U.S.-Russia to other nuclear weapons states (P-5), *de facto* weapons states, non-nuclear weapons states, and NATO.

A nuclear security symposium, in January 2011, organized by the National Academy of Science Committee on International Security and Arms Control (CISAC) and USIP, asked experts from U.S. and Russia to draw lessons from the past and consider what could be accomplished today and in the future. By focusing on science diplomacy in support of nuclear security, they emphasized how science can bridge distrust and work to build meaningful confidence measures between countries. Past efforts, such as the U.S-Russia Joint Verification Experiments (JVE) explored how sensitive national security information could be protected while finding ways to monitor the other side's nuclear tests under the Threshold Test Ban Treaty. In this way, bilateral technical cooperation in support of verification was used to build trust.

The following presentations expanded on the importance of scientific and technical cooperation by describing past verification technology cooperation for the Intermediate Range Nuclear Forces (INF) Treaty and the Comprehensive Nuclear Test Ban Treaty (CTBT). Participants noted additional cooperative programs, not necessarily aimed at a specific treaty, which kept technical experts working together on a broad range of national security topics. The U.S. – Russia Warhead Safety and Security Exchange (WSSX), U.S-UK cooperation, and U.S.-China cooperation on materials protection, control and accounting were cited as examples. The most successful technical efforts focused on problems to develop common approaches, exercising sound scientific principles, and as much as possible, shielding the work from political pressures.

More details were presented on technical work that aided in the development of the CTBT global Radionuclide Monitoring Network (part of the International Monitoring System) and the CTBT On-Site Inspection regime. Experts illustrated how scientists working in a creative environment could cooperate and effectively communicate the results of their work to the policy community for implementation.

Two speakers addressed practical aspects of implementing verification regimes by drawing on U.S. and Russian experiences to implement Strategic Arms Reductions Treaty (START) on-site inspections and a more recent UK-Norway initiative to explore verification of nuclear warhead dismantlement between a nuclear weapons state (NWS) and a non-nuclear weapons state (NNWS). In both cases, a clear understanding of the treaty/policy requirements was needed for successful implementation of the inspections. The tension between protecting the inspected party's sensitive information while allowing sufficient access to provide the inspecting party with confidence that their objective has been achieved was clearly illustrated, and ways to overcome this tension were explored.

The workshop participants were reminded that hosting an inspection is a disruptive event and must be efficiently run with fully functioning equipment. The health and safety of the inspectors must also be considered. It was stressed that in many cases, the simplest equipment might be the best option but if specialized equipment is needed, jointly developed systems provide the highest confidence that access to sensitive information has been controlled and the measurement results are accurate. The START I inspectors benefited from ten years of on-the-ground experience and this experience will be carried forward to the New START inspection regime. The U.K.-Norway Initiative illustrated how the dialogue between sides is crucial in understanding the complexities of bilateral work between a NWS and NNWS. The U.K-Norway Initiative went one step beyond NWS-NNWS engagement and looked at the advantages and disadvantages of engaging the public via a trusted observer (in this case a non-governmental organization). They reported that this was useful in establishing a constructive dialogue.

The final session set out to outline the possible steps to be taken as the world moves from the current nuclear weapons stockpiles levels held by the P-5 to lower levels taking into account existing and potential Indian, Pakistani, Israeli, DPRK, and Iranian weapons. The session highlighted the premise that, as the number of weapons decrease, the cost and intrusiveness of each successive treaty will increase and new authorities and technological approaches will be required. The challenges inherent in accepting an increased level of intrusiveness and the need to verify declarations will have to be taken into account. Additionally, national defense linkages to conventional weapons cannot be ignored as the number of weapons gets lower and lower.

Technical presentations addressed the anticipated difficulties in protecting sensitive information collected during nuclear warhead measurements and consideration for designing information barriers to protect such information. Significant challenges would be encountered if a treaty required chain of custody and accounting of warheads throughout the lifecycle of nuclear operations.

Exercise

The workshop participants were divided into two groups and asked to explore the political and technical requirements needed for states to move towards significant arms reductions. Using a technique called *backcasting*, participants were asked to imagine a world without nuclear weapons and describe what would be needed to achieve levels of one thousand, one hundred, ten, and ultimately zero weapons in the world. The objective was never to convince the participants that a world without nuclear weapons would be achievable in the near future but to encourage thinking about the provisions that would needed to verify such a world. Although many participants could not accept the reality of zero nuclear weapons, a lively discussion ensured. Graphical representation of the discussion was used to help the groups' focus and highlighted some of the diplomatic and technical actions that would likely be needed.

Key Issues Discussed

The intent of the exercise was to stimulate discussion and not arrive at consensus conclusions, especially given the small amount of time and diversity of expertise in each group. For the purpose of this paper, a few of the key issues are highlighted. In each case, the topic could be explored to a much greater depth.

Importance of Political Commitment

Most participants agreed that a strong political commitment will be necessary and that complete disarmament will only be possible if states are convinced that nuclear weapons serve no purpose. Some members suggested that it is wishful thinking to believe that nuclear weapons will be eliminated and equated this with a change in human behavior stating that "humans will always kill humans, it is in our nature." In considering potential government positions, the group identified two factors that will be pivotal to developing national policies: (1) the deterrent role of conventional forces will influence the perception and need for nuclear weapons, and (2) different states pose different proliferation risks so it will be difficult to formulate a universally applied global verification regime. This could influence the level of confidence that could be achieved and complicate implementation of an effective global verification regime.

Beyond the P-5

Russia-U.S. engagement on arms reductions will be the initial priority, however the importance of P-5 engagement will increase. It was recognized that early inclusion of NNWS into the disarmament verification process would build broad confidence that nuclear weapons were actually being dismantled. UK and Norway have taken an initial step in this direction (as presented earlier). There will be a significant challenge to overcome the tension between the increased need for detailed information sharing while preventing design information from being revealed to NNWS. It was suggested that the international community might have to be satisfied with a "black box" approach where a warhead is demonstrated to contain fissile materials upon entering a dismantlement cell and shown a "box of parts" at the end of the dismantlement.

Moving from 1,000 to 100 (Some Concepts and Ideas)

Both groups believed that a period of greater instability would be encountered when moving from 1,000 to 100 nuclear weapons and that it would be imperative to accelerate quickly through this period. A large backlog of weapons designated for dismantlement, but not yet dismantled, would increase instability. Significant dismantlement will likely require dedicated dismantlement facilities in many countries and require firm longer-term political commitment to maintain the activity through this period of instability. In an unstable environment, it is unlikely that states would agree to further reduce their nuclear weapons stockpiles. Some members pointed out that the United States and Russia have not surrendered any strategic capabilities by reaching the current state of the numbers of nuclear weapons. This will change near the period of instability and this will make it difficult, even dangerous, to manage.

Throughout the process of dismantlement, continued monitoring of states and non-state actors to prevent and detect the acquisition and development of nuclear weapons would be needed. Suggestion were made for; (1) an expansion of the "Open Skies Treaty" where mutual aerial observation was agreed to among thirty-four nations as well as a sensor network to monitor and detect facilities; (2) the need for a new Conventional Forces Treaty, based on the CFE (Conventional Forces Treaty in Europe) to prevent a non-nuclear arms race by placing ceilings on non-nuclear weapons; (3) societal verification with cell phones equipped with sensors and sophisticated pattern recognition software to track financial transactions dealing with the transfer and acquisition of materials for a nuclear program; and (4) a verification regime for the PAROS (Preventing an Arms Race in Outer Space) treaty containing remote sensing and on-site inspection components to verify no warheads on ballistic missiles (expected not to be difficult with radiation detectors near the launch site).

The group discussed the need to have an international body monitor the disarmament process to maintain legitimacy for the international community. One possibility could be the development of an intergovernmental panel on verification and disarmament (note that something similar has been proposed by Frank von Hippel in terms of an inter-governmental panel for fissile materials as discussed in P. Lewis, www.icnnd.org/Documents/Lewis_FMCT.doc, p. 15) to monitor and facilitate disarmament. Membership would be expected to include NWS and *defacto* NWS and NNWS to maintain legitimacy.

Dealing with Materials

The groups recognized the problem of fissile material disposition after warheads dismantlement. Controlling fissile materials is important since nuclear material could be a direct route to reconstitution of weapons. Possible solutions discussed were: (1) declare the materials as civilian stocks, place them under IAEA safeguards; (2) establish an international fuel bank of dismantled warheads (based on the "Megatons to Megawatts" program), where a handful of states (P-5) would provide fuel for all states, thereby requiring no further uranium enrichment in NNWS (the reduced need to produce and sell enriched uranium would greatly affect the enrichment industry); or (3) negotiate a HEU agreement (as with a Fissile Material Cut-off Treaty) to outlaw its use in the civilian sector and to tag naval reactor fuel with isotopes to prevent its further use in nuclear weapons.

At Low Numbers

At low numbers of nuclear weapons it will become increasingly important to verify that no nuclear weapon state has a strategic advantage because of its arsenal. Therefore, greater openness, such as revealing the yield and type of weapons to assure all nuclear weapon states of the intention to disarm will be needed. It will be critical to prevent design related information from becoming available to other states in accordance with the Nuclear Nonproliferation Treaty (NPT). For example, specific details on weapon miniaturization will need to be protected from becoming available to less advanced nuclear weapon states. Some members stressed that as the number of nuclear weapons draws down among states committed to disarmament, there will be an increased need for transparency among the weapon states, to the point that it may even be possible to forego the need for information barriers. To be able to increase transparency, suggestions were made for "graded classification schemes" based on the proliferation potential of the knowledge to be shared.

As the number of nuclear weapons dwindle to tens of weapons for each NWS, the requirements for transparency will become even more stringent; type of delivery system and speed in dismantlement will become even more important. Some members suggested that all nuclear weapons will need to be monitored or seen at all times. This need must be balanced against national security vulnerabilities resulting from disclosing the locations of the weapons. Again, the tensions between transparency and revealing too much information will have to be carefully managed.

When the point of zero nuclear weapons is reached, the challenge will be to maintain a chain of custody of all fissile materials and the universal safeguards of proliferation-sensitive facilities. This will require a strong financial commitment by the international community since this would need to be maintained in the long term. In principle, a lot of the social and political technological challenges will already be solved in order to get to this point. However, dealing with dual-use and latent capabilities together with the need to control any release of sensitive national security or weapons significant information will greatly complicate the process. Some members of the group observed that once nuclear weapons will become devalued in society they will still pose an inter-generational danger, and it will be important not to become complacent and maintain chain-of-custody in perpetuity.

Conclusions

An INMM workshop to address technical transparency and verification challenges in preparing for nuclear arms reductions brought together about seventy international multi-disciplinary experts from government, international organizations, non-governmental organizations, national laboratories, industry, and academia. The mix of policy and technology experts, together with students resulted in lively discussions and the group was motivated to explore various options, and identify obstacles and technology challenges. Student participation allowed engagement between those embarking on their careers with those who have had decades of experience working on nuclear weapons issues. The presentation materials will be available on the INMM Web site and ideas for follow-on workshops and studies are being explored.

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Taking the Long View in a Time of Great Uncertainty

Focusing on the Future of Safeguards and Nonproliferation

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

Ken Sorenson, INMM Vice President, in collaboration with Jim Larrimore, INMM International Safeguards Technical Division Chair, and Michel Richard, Co-Chairs for the 7th INMM/ESARDA[1] Joint Workshop

Introduction

I am pleased once again to provide a guest column opportunity in this edition of the *JNMM* for Ken Sorenson, INMM vice president, to report on the recent 7th INMM/ESARDA Joint Workshop, *Future Directions for Nuclear Safeguards and Verification*, held in Aix-En-Provence, France, on October 17-20, 2011. Not only were the topics of this workshop pertinent to *Taking a Long View in a Time of Great Uncertainty*, but the workshop itself reflects an important strategic initiative by the Institute to strengthen the collaborative environment with other organizations worldwide that are dedicated to nuclear safety and security and the promulgation and enhancement of scientific and engineering knowledge of things nuclear.

Looking Back and Looking Forward

For an organization to succeed in planning, it must have a thorough understanding of the past and how it arrived at its current state, as well as the ability to "connect the dots" of current events to understand what future worlds may be in the offing. In the one short year this column was refocused on the future, we have examined, in an historical context, the critical uncertainties that are facing the Institute and its membership from both without and within, including:

- The dramatic expansion of nuclear power worldwide and the attendant nonproliferation and safety issues associated with that expansion.
- The increasingly unstable international security environment with respect to Iran's surreptitious nuclear program and the growing concern by many countries of the consequences of those actions.
- The continuing intransigence of North Korea with respect to its nuclear program, and the proliferation consequences.
- The growing anxiety over the security of Pakistan's nuclear stockpile and the long-term stability of its government.
- The global economic crisis.
- The political and international security turmoil resulting from the "Arab Spring" that now appears to be continuing into 2012.
- The strategic worldwide impact of the Fukushima Daiichi nuclear power plant accident in the aftermath of the March 11, 2011, earthquake and tsunami that devastated northern Japan.
- The restructuring of the Institute's organization to address the changing needs of our community.
- The changing face of the Institute with the aging of many of its longer term members, and the rise of a new generation of technology-enabled members from our student chapters and elsewhere.

As we enter 2012, the world continues to face complex challenges, with consistent statements by political leaders and policy makers that the threat of nuclear proliferation and the spread of nuclear material to non-state actors remain the single most important global security issue. In that context, to support President Obama's efforts to rally world leaders and public opinion toward the task of securing nuclear materials, reducing reliance on nuclear stockpiles, and safeguarding nuclear know-how, much remains to be done. It is in this context that the topics of the recent joint INMM/ESARDA workshop on the future directions of nuclear safeguards and verification exquisitely represent the continuing importance and leadership of these two international organizations to address the uncertainties that lie ahead.

The Future of Safeguards and Nonproliferation

IAEA safeguards evolution to the state level approach; state and regional systems (SSACs[2]/RSACs[3]); triple-S[4] culture; safeguards by design; monitoring and verification; detection of undeclared activities; open sources; irreversible nuclear disarmament and verification; global zero; synergies between treaty regimes; and education and training. These were the key topics discussed in depth at the 7th INMM/ESARDA Joint Workshop.

For each INMM/ESARDA joint workshop, a particular theme associated with safeguards, verification, and nonproliferation is chosen. With the growing interest in the commercial nuclear fuel cycle, efforts to reduce existing nuclear weapon stockpiles, the prospect of a fissile material cut-off treaty, advances in technical and facility capabilities in non-nuclear-weapons states, and the severe accident at Fukushima, the focus for the 7th joint workshop on looking to the future in safeguards and verification R&D was timely. James Larrimore and Michel Richard teamed together as workshop chairs to structure a program that sought to develop a deeper understanding of the rapidly changing and complex issues we are facing today and must address in the near-term future.

The workshop consisted of four parallel working group sessions with an opening plenary session kickoff and a closing plenary session to provide the summary and conclusions. The four working groups and their chairs were:

- Future Directions for International Safeguards; Jim Casterton (IAEA[5]) and Paul Meylemans (EC[6]), co-chairs
- Future Directions for Safeguards & Verification Technology and R&D; Diana Blair (Sandia National Laboratories) and Sergey Zykov (IAEA), co-chairs
- Broader Perspective on Nonproliferation and Nuclear Verification; Mona Dreicer (Lawrence Livermore National Laboratory) and Gotthard Stein (Germany), co-chairs
- Education and Training; Willem Janssens (EC) and Melissa Schultz (DOE/NNSA[7]), co-chairs

The workshop chairs put together the speaker program, assisted by working group co-chairs, who were tasked to lead their two days of sessions and report out at the closing plenary. The speakers were top professionals in their fields, which stimulated and enlivened the discussions. To summarize three and one-half very full days:

- The International Safeguards Working Group supported and encouraged the IAEA vision towards a state level approach for management and oversight of international safeguards.
- The Safeguards & Verification Technology and R&D Working Group discussed traditional, as well as non-traditional concepts, and hardware and software approaches to monitoring and verification.
- The Nonproliferation and Nuclear Verification Working Group grappled with the nuclear regimes and their interplay amongst all the states involved, nuclear weapon states as well as non-nuclear weapons states.
- The Education and Training Working Group took up where they left off at the 2008 INMM/ESARDA Tokyo Workshop with a strong list of actions to further develop this important area. One element that was common in their list of Action Items was the need for INMM and ESARDA to work together in this area.

The opening plenary put the focus of the workshop in context for the rest of the week. Herman Nackaerts, deputy director general of the IAEA Safeguards Department, provided a frank history of IAEA implementation of safeguards and identified concrete suggestions for moving forward in the future to make international safeguards more effective and efficient. Nackaerts' talk was followed by Piotr Szymanski, EC/Directorate General for Energy, director, head of the Directorate for Nuclear Safeguards, who described the role of EURATOM in NNWS[8] and NWS[9] European Union member states and stressed the importance of the cooperation between EURATOM and the IAEA; and Philippe Delaune and Etienne Pochon, both of CEA,[10] who presented perspectives on international safeguards from an active IAEA and EU[11]-member country.

The closing plenary began with reports by the chairs of each working group. Each report provided a succinct overview of the working group discussions to all the participants. These working group reports will be made available through INMM and ESARDA websites, and will be included in the workshop proceedings, which will be prepared by ESARDA. These reports were followed by a compelling talk from Jacques Ebrardt, CEA, Dismantling the Fissile Materials Production Plants for Nuclear Weapons: A French Perspective. This talk covered the entire dismantling and restoration of the French materials production capability including the French nuclear testing site in the South Pacific; starting from the two atmospheric test sites in the Pacific, to the uranium enrichment facility in Pierrelatte, to the three Pu production reactors and associated reprocessing plant in Marcoule. Ebrardt stressed that this commitment by France was unilateral, transparent, and irreversible.

From an INMM perspective, this workshop highlights the importance of INMM's relationship with ESARDA. INMM attendees at this meeting included the vice president, three members of the Executive Committee, the chair of the Technical Division Oversight, the chair of the International Safeguards Technical Division, and the chair of the Nonproliferation and Arms Control Technical Division. Of course, numerous INMM members gave presentations and participated, including ESARDA members who are also INMM members.

Recognizing the importance of the INMM/ESARDA relationship, an initiative began last May to develop a more formal relationship between the two bodies. A sidebar meeting was held at this workshop to finalize a draft Letter of Intent (LOI) that will provide a framework to strengthen and expand our working relationship. This LOI must receive approval of both governing bodies. Stay tuned for further developments.

One other development of note that occurred at this workshop was the establishment of a new INMM working group under the International Safeguards Technical Division that will focus on geospatial and open sources as technologies that need to be addressed in the future of safeguards and verification.

In conclusion, the workshop was a tremendous success. Thanks to ESARDA, the CEA, and the JRC[12] for sponsoring the workshop and for the workshop chairs for putting together and staging such a timely and productive meeting. The future of international safeguards and verification is now, and the need to act is compelling.

Strengthening the Role of the Institute Through Collaboration

Collaborative efforts such as those described here with ESARDA, and with other organizations such as World Institute for Nuclear Security (WINS), and the American Nuclear Society (ANS) will help strengthen INMM strategic objectives in meeting its mission. During the coming year, the Strategic Planning Committee will be examining the impact of these collaborations to better understand how they can be leveraged in support of our mission. Membership of the Institute is welcomed to provide information on their collaborative efforts and suggestions to the author.

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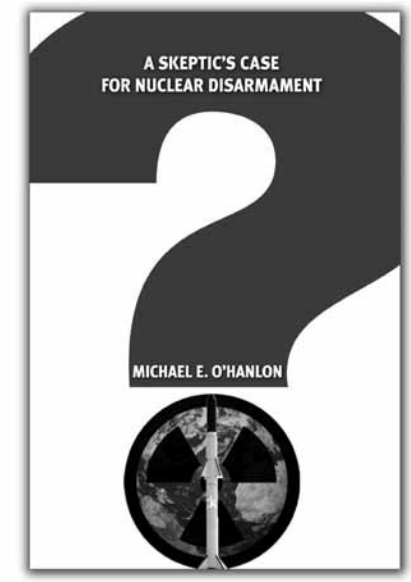
End Notes

1. ESARDA: European Safeguards Research and Development Association
2. SSAC: State System of Accounting and Control
3. RSSA: Regional System of Accounting and Control
4. Triple-S: Safety, Security and Safeguards
5. IAEA: International Atomic Energy Agency
6. EC: European Commission
7. DOE/NNSA: U.S. Department of Energy's National Nuclear Security Administration
8. NNWS: Non-Nuclear Weapons States
9. NWS: Nuclear Weapon States
10. CEA: Commissariat a l'Energie Atomique (French Alternative Energies and Atomic Energy Commission)
11. EU: European Union
12. JRC: ESARDA's Joint Research Centre

Book Review

By Mark L. Maiello

A Skeptic's Case for Nuclear Disarmament
Author: *Michael E. O'Hanlon*
ISBN 978-0-8157-0507-9



When considering total nuclear disarmament, a case can be made for a measured, gradual reduction that considers the foreign policy situation of the United States and the state of the planet's potential military flash points that affect American security and those of its allies. The nation's future needs for defense through possession of nuclear arms coexist with the goals of the Nonproliferation Treaty for reduction and eventual elimination. If a systematic approach is used that considers security needs while pursuing arms reduction, virtual elimination might be possible. By and large, this argument sounds appealing because it advocates reduction but does so outside the vacuum of more narrowly focused discussions that commonly call for abolition based solely on the inhumanity and amorality of nuclear weapons. For this perspective alone, *A Skeptic's Case for Nuclear Disarmament* is worth a read. Author Michael O'Hanlon, a Brookings Institute senior fellow and expert in national security, methodically presents this pragmatic discussion in six concise chapters that emphasize the reality of the world's geopolitical crises, the associated effects on national defense policy, and the influence it has on the abolition of nuclear weapons.

In presenting his version of disarmament with considerations for a realistic defense posture, O'Hanlon quite necessarily opens with a description of the nuclear abolition movement that includes arguments for and against its attainment. It is here, up front, that the reader is made to understand that disarmament is both a laudable goal and unless approached carefully, a chimera. He presents the opposing arguments—both strong and compelling—for maintenance of a nuclear weapons capability and for the moral necessity to reduce nuclear arsenals to zero. How to move forward? What must world policy makers consider to reach the abolition finish line while weapons are still deemed necessary to maintain defense? Part of O'Hanlon's answer is that a zero-weapons treaty cannot withstand the stresses of real world politics unless it provides for a temporary withdrawal from the agreement under threat of catastrophic attack by an aggressor. In fact, the aggression need not be via nuclear weapons. The author points out that a well-designed biological pathogen with an antidote known only to the aggressor nation is a sufficient threat for treaty withdrawal. A nuclear weapons response would be swift enough or deemed devastating enough to curtail such a mass casualty biological attack.

The next two segments of the book discuss in greater detail the ideas of chapter 1 through a review of the reasons to eliminate nuclear weapons followed by a summation of why that elimination is not practical. The former discussion is very useful for its overview of the historical events that almost culminated in the use of nuclear weapons. These include accidents involving weapons, a discussion of the vulnerability of command and control systems and the current worries over terrorism and proliferation. The latter chapter on impracticality is founded on such topics as the difficulties of verification, the limitations of conventional armaments vs. nuclear weapons, the aforementioned threat from biological warfare, and an explanation about U.S. nuclear disarmament and the potential adverse affect it may have on proliferation (by creating insecurity in nations currently protected by the U.S. nuclear umbrella).

Chapter 4 is the heart of the book where O'Hanlon solves the paradox created by the conclusions that nuclear weapons are too dangerous to live with yet impossible to totally eliminate. The solution, explained lucidly in twenty-six pages, is to dismantle the weapons rather than destroy them. He presents a time frame for discussion of the associated weapons treaty largely based on resolution of the major world crises so that global national security is enhanced (and nuclear weapons are less of a need). As he himself indicates, nuclear disarmament is not on the horizon given the large number of existing international disputes. But, assuming that higher level global security crises are resolved, he suggests that a treaty be negotiated that bans nuclear weapons, catalogs and monitors all related nuclear material, goes into effect only when the treaty is ratified by all nuclear-weapons states and only when a well-funded (to the tune of $1 billion a year) watchdog agency is established. O'Hanlon's critical argument here is that withdrawal from the treaty for the purpose of reconstituting a temporary nuclear arsenal for defense against clear aggression is key to success. Again, pragmatism rules the day: the ability to build a nuclear weapon will never be lost and a treaty cannot erase that knowledge. It is more productive to embrace this concept and use it as an asset. Since no one can be certain if nuclear weapons can ever be effectively and permanently banned, why seek that prize at all? Instead, write into the treaty the ground rules for rebuilding an arsenal should a nation be required to do so. Should they never be needed, the ban could evolve into the standard operating regime for the planet. What O'Hanlon effectively proposes is dismantling—not abolition—but with good cause.

To round out his dissertation, O'Hanlon presents a near-term agenda to prepare the way for a disarmament treaty. He spells out the need for ratification of the Comprehensive Test Ban Treaty, and discusses why Russian and American nuclear deterrence need not be harmed by a reduction of offensive weapons to 1,000 total warheads each. He also presents the ideas of minimizing the importance of nuclear weapons in national security policies and seeking cooperation between nations on the issue of missile defense. This is a contentious issue between Russia and the United States made obvious when the latter recently proposed placing such defensive systems in Poland and the Czech Republic.

For the novice or student, this is an excellent book to acquire. O'Hanlon's use of English is easy-going and by no means heavy handed. He speaks plainly to the reader without the use of too many acronyms. The technical jargon will be readable and understandable by even those new to the subject matter. The pace of his discussion is very pleasing. He completes the book in a mere 144 pages. For the scholar, there are an additional twenty-one pages of notes and references and a good usable index. Instructors of global policy, international studies or nonproliferation may easily judge this book to be good supplementary reading for their students.

One of the high points of the book is O'Hanlon's practical approach to the problem that relies on his scholarship in international security and defense—for that is the linchpin to the matter. Insecurity often breeds the desire (or excuse) for nuclear arms. At least it is part of the equation. His argument that global insecurity should be brought to a practical minimum before a treaty can be had seems sound—if not a bit utopian (but what talk of total disarmament isn't to some degree?). He frankly poses the question: How else can significant, steady, and long-term arms reduction occur if not in a world-environment of relative stability? There is also value in O'Hanlon's concise overview of the near-miss nuclear crises of the past for the compelling realization (needing repetition) that living without consequences due to the existence nuclear weapons is not sustainable.

The efficient manner in which this book conveys its message and the attainable language it uses to do so engages the reader and effectively communicates the fine points of a complicated and important debate in short order while providing useful nonproliferation background information. This is a valuable and thoughtful contribution to the discussion of total nuclear disarmament. It takes into account—and I think in a fair, balanced way—the arguments both for and against while ultimately concluding that attaining zero is possible—if carefully timed and seriously nurtured.

Mark L. Maiello is a health physicist with interests in radiological and nuclear security. His writing has appeared in these pages and that of Health Physics, Health Physics News*, and other related technical publications.*

Book Review

By Walter Kane
JNMM *Book Review Editor*

Fuel Cycle to Nowhere: U.S. Law and Policy on Nuclear Waste
Authors: *Richard and Jane Stewart, Vanderbilt University Press, Nashville, Tenn.*
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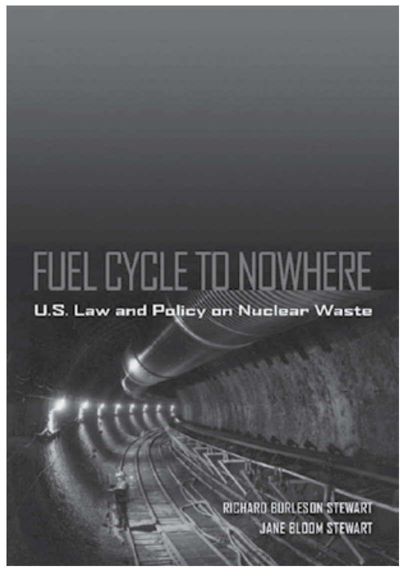

There are two varieties of calamity that overtake humanity; those with a natural origin such as earthquakes, tsunamis, hurricanes, and floods, and man-made calamities such as fiscal crises, the terrible wars of the twentieth century, and global climate change. The crisis we are facing with respect to the management and disposition of spent nuclear fuel and other radioactive waste meets the definition of a man-made calamity. This crisis is the principal obstacle today to the adoption of a carbon-free energy source that produces twenty-five tons of waste per year in contrast to a fossil fuel plant, which produces millions of tons of CO_2 and 700,000 tons of toxic coal ash per year. Spent nuclear fuel has been accumulating in cooling ponds and dry cask storage for decades. It is a valuable resource since the once-through fuel cycle (the cheapest solution) utilizes only one percent of the available energy in the original uranium.

In *Fuel Cycle to Nowhere* Richard and Jane Stewart address in detail the sixty-year history of our nuclear waste laws and policies, nuclear waste classification and regulation, low-level waste disposition and regulation, and the history of the Waste Isolation Pilot Plant – also known as WIPP (a successful facility), and Yucca Mountain (an expensive failure).

Fuel Cycle to Nowhere is a valuable resource for all those concerned with the future of nuclear energy and the grave threat of global climate change driven by fossil fuel consumption. In particular, the last chapter, "Lessons Learned and Future Choices" is a valuable guide to "doing it right next time." The successful history of WIPP, where state and local governments and citizen stakeholders were continually informed and enabled demonstrates that it is possible to manage nuclear waste in a politically and technically appropriate manner.

During this year, the Journal of Nuclear Materials Management *celebrates its 40th anniversary. As part of that celebration, we will reprint some of what we consider to be our more significant articles from the past forty years.*

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The LASL—U.S. ERDA NDA Training Program

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I. Introduction

A wide variety of new nondestructive assay (NDA) instruments and techniques are required to measure, safeguard and control special nuclear materials (SNM) in the many different chemical and physical forms in which they are found throughout the nuclear fuel cycle. The transfer of NDA technology from the instrument development laboratory to various types of plants and facilities in the nuclear fuel cycle is an important part of the Los Alamos Scientific Laboratory's Research and Development Program in Nuclear Safeguards. To implement this technology transfer, the U.S. Energy Research and Development Administration has established at LASL the U.S. ERDA Nondestructive Assay Training Program, which is now available to essentially all qualified users (in both government and private sectors) of NDA equipment for the measurement and control of fissionable material. The present curriculum consists of a one-week course in basic passive gamma and neutron assay, emphasizing the use of portable instrumentation, and a more advanced course (one-week duration) in high resolution gamma-ray assay. An advanced neutron assay course may be made a part of the curriculum when the demand merits. The goal of these courses is to teach specific principles and practical skills which are essential to both the inspectors and the plant personnel who are responsible for conducting various assay and verification measurements.

Each course is laboratory and instrumentation oriented, with lectures covering basic theory, instrument operation, and potential problem areas. Manuals have been written which serve both as textbooks and as general reference sources. Laboratory groups are kept small (3 to 5 persons), each group having their own instrumentation. LASL instructors interact closely with the attendees, not only on the assigned course work, but also in sharing experiences gained in field-implementation of NDA techniques.

The basic course has been presented three times, the advanced course once, with a total attendance of 92 persons, representing a wide variety of U.S. government and industrial organizations (about 80% of the attendees) as well as the International Atomic Energy Agency (about 20%). This spring (May 17-21,1976) the advanced course will be given for the second time with the enrollment limited to twenty.

Figure 1. Outline of the introductory course

FUNDAMENTALS OF NONDESTRUCTIVE
ASSAY USING PORTABLE INSTRUMENTATION

- A. Gamma-Ray Assay Techniques
  - 1. Fundamentals
    - a. U and Pu spectra
    - b. Detector operation
    - c. Attenuation
    - d. Statistics of counting
  - 2. Enrichment Measurements
  - 3. Quantitative Assay-Transmission Based Attenuation Corrections
- B. Neutron Assay Techniques
  - 1. Fundamentals
    - a. Neutron production, detector operation
    - b. Matrix effects, neutron scattering
  - 2. Assay Techniques
    - a. SNAP measurement of Pu metal buttons
    - b. Measurement of mixed oxide fuel rods
    - c. UF_6 measurement
- C. Demonstrations
  - 1. Random Driver
  - 2. Neutron Well Coincidence Counter

II. The Curriculum

A. Fundamentals of Nondestructive Assay Using Portable Instrumentation.

This course is designed as a basic introduction to the principles and techniques employed in passive gamma ray neutron assay of fissionable material. A brief course outline appears in Fig. 1. The text for the course "Fundamentals of Passive Nondestructive Assay of Fissionable Materials" by R.H. Augustson and T.D. Reilly[2] [1], covers the basics of gamma ray and neutron production, interaction and detection and the application of these basics to the NDA of special nuclear material. Among the topics discussed in detail in the text are: gamma- ray production and interaction with matter, gamma ray detectors, analysis of gamma ray pulse-height spectra, quantitative gamma-ray assay, enrichment measurements, neutron production and applicable signatures, neutron detectors and neutron verification measurements.

Introductory lectures, based on the text, are given at the beginning of the gamma-ray and neutron sections of the course. In the laboratories, the class is divided into small groups of three to five students, each with an individual instructor. Instructors provide detailed discussion/clarification to these smaller groups as warranted (Fig. 2). The laboratory exercises have been pub-

Figure 2. An informal lecture by LASL instructor T. Canada.

Figure 3. Some of the equipment used in the introductory course. From right to left: Ge(Li) detector, multichannel analyzer, SAM-II, NaI detector, and oscilloscope.

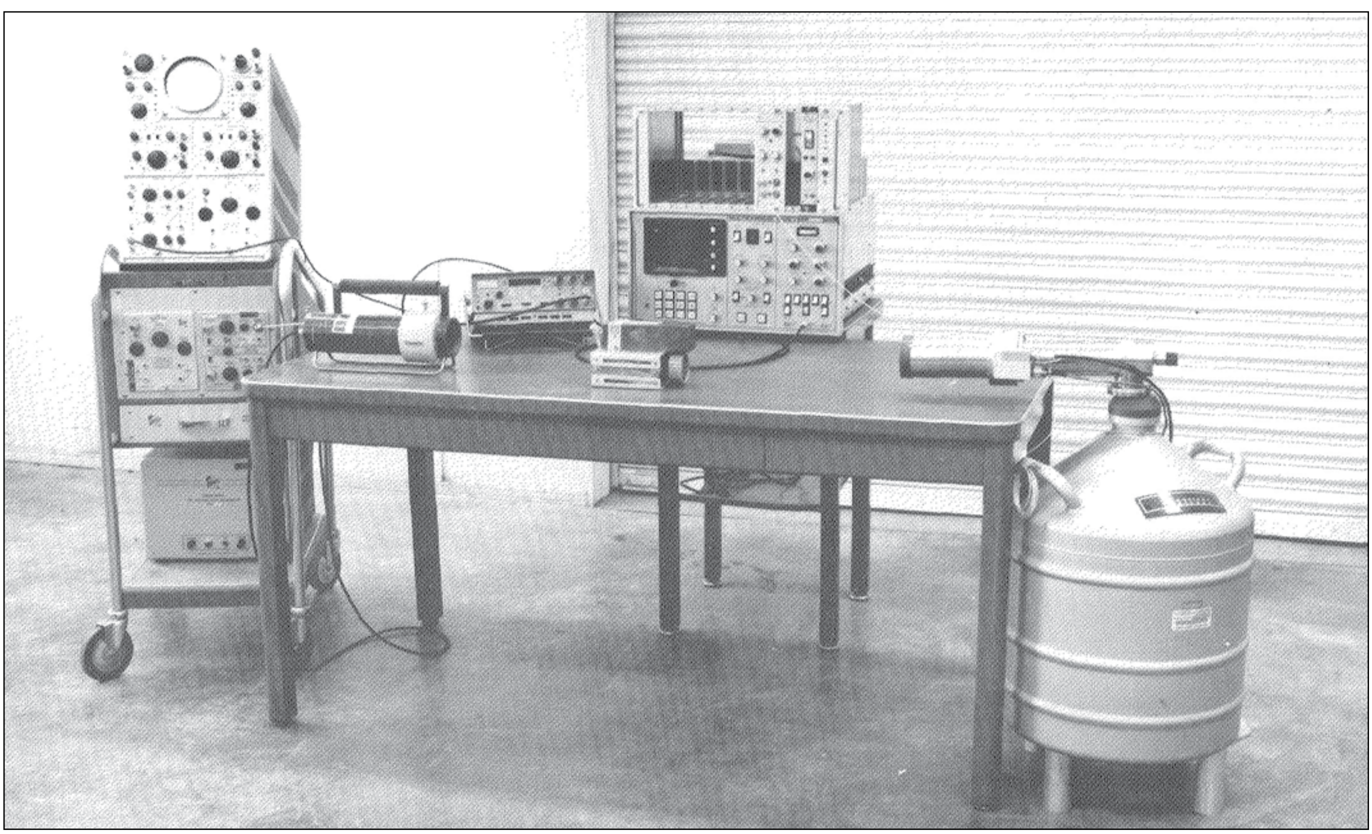
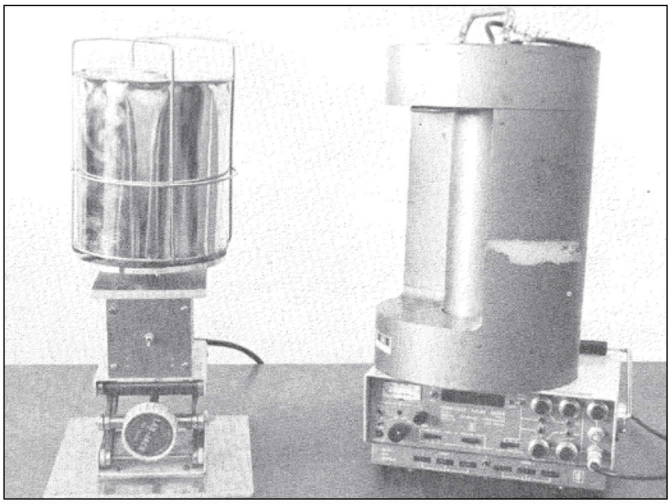


Figure 4. SNAP neutron detector and one of the sample matrix containers used in the introductory course. A series of such cans is used to show the effect of different materials on the neutron energy spectrum and detector response.



lished in a workbook supplement to the main text. These exercises emphasize the use of portable instrumentation but expose the student to a variety of more sophisticated laboratory equipment and procedures (Fig. 3), including multichannel analyzers, Ce(Li) detectors, and oscilloscopes.

The quantitative gamma-ray assay exercises, performed with Nal detectors and the SAM-II,[2] include the measurement of plutonium in incinerator ash (using an external transmission source), holdup measurements, and enrichment determinations of UO_2 standards and UF_6 product cylinders. The neutron assay laboratories, using a SNAP detector system [2] (Fig. 4), deal with the assay procedures for plutonium metal buttons, samples of bulk plutonium oxide, mixed oxide fuel and UF_6 cylinders.

Although the course emphasizes "hands-on" experience in small groups, several demonstrations of more advanced instrumentation are given. Typical demonstration topics are spontaneous fission neutron coincidence counters [3], low-level effluent monitors [4], and the Random Driver [5] active neutron interrogation system.

B. Gamma-Ray Spectroscopy for Nuclear Material Accountability.

The purpose of this more advanced course is to familiarize the students with the powerful techniques available for NDA of SNM using high resolution gammaray detectors. A brief course outline is given in Fig. 5. The course text [6], laboratory exercises, and lecture presentations are designed to emphasize the basic techniques of high resolution gamma-ray spectroscopy and the fundamental principles involved in various NDA measurements. Particular emphasis is placed upon the limits of applicability and the achievable accuracies of those measurements.

Figure 5. Outline of the advanced course on gamma-ray assay techniques.

GAMMA-RAY SPECTROSCOPY FOR
NUCLEAR MATERIAL ACCOUNTABILITY

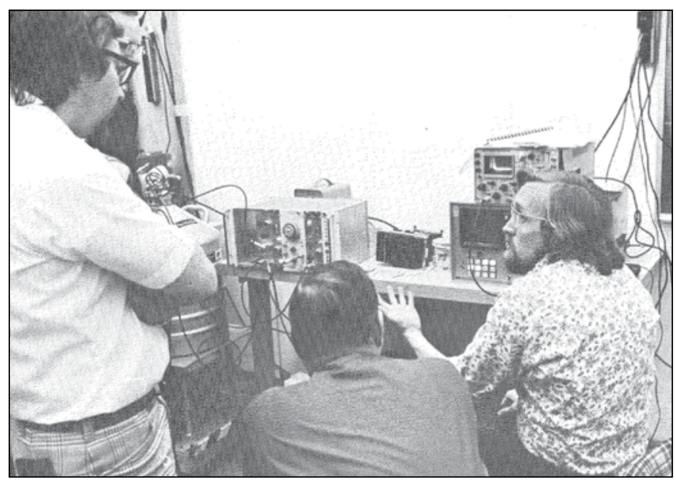
A. General Techniques of Gamma-Ray Spectroscopy
   1. Optimization of resolution
   2. Count rate effects
   3. Statistics of counting measurements

B. NDA Techniques
   1. Sample counting
   2. Corrections for self-attenuation
      a. Differential absorption
      b. External source transmission
   3. Gamma-ray densitometry
   4. Enrichment measurements

C. Applications of Principles

D. Demonstration of Automated Gamma-Ray System

Figure 6. LASL instructor, R. Augustson, explains enrichment measurement procedures to laboratory group. A Ge(Li) detector system is used to measure a series of cans filled with UO_2 of differing enrichment.



As in the fundamentals course described above, the laboratories are designed to accommodate small student groups and thus to emphasize the "hands-on" experience. Each group conducts assays with a number of detectors (small planar and large coaxial Ge(Li), intrinsic Ge), coupled to a variety of sophisticated data collecting systems (Fig. 6). Assays are made on a number of uranium and plutonium samples, including solutions with densities of SNM of from 1 to 400 g/l, plutonium mixed with low Z solids, and pure (JO_2 with varying enrichment. The assay techniques used include: direct comparison of sample gamma activity with standards, correction for sample attenuation by the differential absorption of sample gamma rays [7, 8] or the transmission of an external gamma-ray source [9], the determination of total uranium or plutonium content by gamma-ray densitometry [10], and enrichment measurements [11]. As an example of the ap-

Figure 7. LASL instructor, D. Reilly, demonstrates operation of a segmented gamma scan (SGS) system. The pictured system is a versatile data acquisition system for laboratory use. Dedicated SGS systems are much smaller and simpler to operate.

plication to state-of-the-art instrumentation of some of the principles taught in the laboratories, a detailed demonstration of a fully automated segmented gamma scanner [12] is given (Fig. 7).

III. Discussion

The interests, viewpoints and problems of various groups or agencies in the application of NDA technology are diverse. The inspection and verification safeguards problems of NRC, U.S. ERDA operation offices, and the IAEA can be quite different from those of production facilities, where the major concern is with plant output, product control, and simply meeting safeguards regulations. Knowledge of these problems is essential to viable research and development laboratory programs. These courses provide an opportunity for an exchange of these differing viewpoints and the discussion of the associated problems.

The interaction does not end with the completion of the formal courses. Rather they serve as a foundation for future consultations on new or complex assay problems. The texts for the training program courses—over 700 copies of which have been distributed—have broadened significantly the number of individuals involved in these consultations.

Technology transfer is an important yet difficult process requiring the active involvement of all parties. The ERDA Nondestructive Assay Training Program has proven to be an effective method of bridging the gap between the NDA instrument developer, the safeguards and accountability inspector, and the in-plant user of nondestructive assay equipment.

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