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INMM Milestones

By Nancy Jo Nicholas
INMM President

This is a year for everyone in the field of nuclear materials management to reflect on decades of remarkable achievements. In mid-November, I had the distinct pleasure and honor of speaking at the Japan Chapter of the Institute of Nuclear Materials Management's annual meeting, which celebrated that chapter's thirtieth anniversary. The participants and invited guests looked back with pride at the thirty years of fruitful efforts by nuclear material management experts. I also visited several Japanese nuclear facilities, including the Joyo reactor, which recently celebrated its fortieth year of operation.

Last fall I represented INMM in Vienna at the International Atomic Energy Agency's 10th Symposium on International Safeguards, an outstanding event that was a highlight of the year-long celebration of the IAEA's fiftieth anniversary. INMM and the European Safeguards Research and Development Association (ESARDA) helped the IAEA to organize the International Safeguards Symposium. As a contribution to the success of the symposium, the Japan and Vienna INMM chapters co-sponsored an evening reception at which participants enjoyed an opportunity to meet informally.

The IAEA was formed when its statute was approved at the United Nations Headquarters in New York on October 23, 1956, by eighty-one UN member countries. This IAEA statute entered into force on July 29, 1957. The IAEA has made a remarkable difference in the world of nuclear materials management. During the Safeguards Symposium, I was pleased to be able to speak for everyone in INMM in congratulating Director General El Baradei and the entire IAEA, both for their tremendous accomplishments and their much-deserved recognition by the Nobel Committee in 2005. This is an extraordinary achievement, and one in which everyone who labors in the field of nonproliferation can share. I am proud of INMM's many years of partnership with the IAEA. For the past ten years, INMM has enjoyed nongovernmental organization observer status at the IAEA General Conference.

At Los Alamos National Laboratory, we are celebrating forty years of nuclear safeguards, particularly in development of measurements using nondestructive assay techniques and nuclear material accounting systems. The founder of the safeguards programs at Los Alamos, G. Robert Keepin, who served as INMM chair in 1979-1980, was instrumental in creating many of the safeguards concepts still used today. Keepin and *JNMM* Technical Editor Dennis Mangan were recently honored for their contributions to nonproliferation at the American Nuclear Society Winter meeting in Albuquerque.

In 2005 the Treaty on the Nonproliferation of Nuclear Weapons, or NPT, reached the thirty-fifth anniversary of its entry into force. The objectives this landmark international treaty are to prevent the spread of nuclear weapons and weapons technology, to foster the peaceful uses of nuclear energy, and to further the goal of general and complete disarmament. The NPT establishes a comprehensive safeguards system under the responsibility of the IAEA.

The Institute of Nuclear Materials Management is about to achieve yet another important milestone. The INMM was formed on May 17, 1958. Dr. Ralph Lumb was elected the first chair of the INMM in October 1958. We are now forming an *ad hoc* committee to plan a year-long celebration of the INMM's fiftieth anniversary. I would like to see this committee solicit input broadly from our INMM members, then establish a theme and help plan a series of events that will be held over a year-long period to commemorate the occasion, culminating with the 50th INMM Annual Meeting, which will take place in July 2009. These are exciting times, and INMM members are on the forefront.

PATRAM 2007

INMM is again proud to host PATRAM, formally known as the 15th International Symposium on Packaging and Transportation of Radioactive Materials. PATRAM 2007 will bring together experts from government, industry, and research organizations worldwide to exchange information on all aspects of packaging and transporting radioactive materials around the globe.

Visit the PATRAM Web site at www.patram.org for program and registration information. Our thanks to the Packaging and Transportation Technical Division and its chair, Ken Sorenson, for their hard work on this important event.

If you have comments, ideas, or questions about INMM, contact INMM President Nancy Jo Nicholas at njnicholas@lanl.gov or: n.j.nicholas@earthlink.net or contact INMM headquarters at inmm@inmm.org.

GNEP and WINS Make Progress

By Dennis Mangan
Technical Editor

It appears that the Global Nuclear Energy Partnership that was announced by President Bush (February 6, 2006) may be gaining momentum. It was a topic at this year's inter meeting of the American Nuclear Society held in Albuquerque and more meetings are being held by various government organizations regarding roles and responsibilities. I understand that at our upcoming annual meeting in July 2007 there may be sessions devoted to this topic, which I believe is definitely appropriate.

Two INMM Past Presidents Honored *— On November 14, 2006, at the American Nuclear Society 2006 Winter Meeting and Nuclear Technology Expo, the ANS Trinity Section presented special awards to two former presidents and current Fellows of the INMM, Dr. G. Robert Keepin (left) of Los Alamos National Laboratory (retired) and Dr. Dennis L. Mangan of Sandia National Laboratories (retired). The awards, in recognition of more than forty years of work by each in the areas of safeguards, security, and nonproliferation, were presented at the General Chair's Special Session on Nonproliferation and Security.*

In response to the challenge given to the INMM by Nuclear Threat Initiative President Charles Curtis in the Plenary Session of our 2005 Annual Meeting (see *JNMM* Volume 34, Number 1, Fall 2005), the INMM and NTI have joined forces to pave a path forward. A concept referred to as WINS (World Institute of Nuclear Security) has evolved and progress is being made. I believe in the near future there will be an update on our Web site, and there are plans in the works to have a special session also at the upcoming annual meeting.

In this issue of the *Journal* we have three papers. The first deals with the important topic of quantifying proliferation risk in nuclear fuel cycles. This paper, *Development of the Nonproliferation Assessment Tool (NAT) Software Package for the Calculation of Proliferation Resistance Values of N;uclear Fuel Cycle Facilities,* is co-authored by three students from the University of Texas, Austin, Texas, USA. This topic is important for decision makers addressing paths to take in near approaches to the nuclear fuel cycle.

The second paper, *Non-Destructive Assay of Nuclide Composition in Spent Fuel from a Research Reactor by Repeat Irradiation and Gamma-Spectrometric Measurement,* by A.V. Bushuev and colleagues from the Moscow Engineering Physics Institute in Moscow, Russia, presents a method for the determination of certain isotopes in spent fuel of a research reactor. Their approach is cleaver, and they conclude that their proposed method is superior to other non-destructive methodologies both in accuracy and the scope of information available about the nuclide composition of spent fuel.

The final paper is by John Darby of Sandia National Laboratories in Albuquerque, New Mexico, USA. In his paper, *Evaluation of Risk for Acts of Terrorism Using Belief and Fuzzy Sets,* Darby lays out an approach that is definitely interesting. Defining risk is key for decision makers, and applies especially to the concerns that the U.S. Department of Homeland Security has regarding the allocation of resources. I believe Darby did a very nice job discussing his approach using fuzzy sets. He gives examples and follows a logical approach. I have been exposed to fuzzy logic approaches before and could never quite grasp the logic. Darby's paper came a long way in attempting to help me understand, but I'm not yet ready to take a final exam on this technology.

On a personal note, I was honored to receive, along with INMM past president and Fellow Bob Keepin, a special award presented by the Trinity Section of the ANS at their winter meeting (see photo). To be on the same stage with "Mr. Safeguards" from Los Alamos was indeed an honor.

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

JNMM Technical Editor Dennis Mangan may be reached by e-mail at dennismangan@comcast.net

Development of the Nonproliferation Assessment Tool (NAT) Software Package for the Calculation of Proliferation Resistance Values of Nuclear Fuel Cycle Facilities

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University of Texas, Austin, Texas, USA

Abstract

Quantitative assessment methodologies have been developed and applied to evaluating the proliferation resistance (PR) of nuclear fuel cycle (NFC) facilities. A literature review of quantitative assessment methodologies for assessing PR of NFC facilities has concluded that

- Methodologies have not been continuously applied over an extended amount of time (longer than two years), and
- Methodologies have not in the past developed or used a graphical user interface (GUI) for data collection, and
- Singular methodologies have not undergone continuous improvement due to continual application of the methodology.[7]

As a result, a software package, the Nonproliferation Assessment Tool (NAT), has been developed, tested, and released by a project team from the University of Texas in Austin (UT-Austin). The project team, consisting of nuclear engineers and computer scientists, executed the software logic design and programming for a seventeen-month period, from January 2004 through May 2005. This project team was funded by the Oak Ridge National Laboratory, Nuclear Science and Technology Division, International Safeguards Group. The Multi-Attribute Utility Analysis (MAUA) approach to proliferation resistance (PR) assessment previously published by William Charlton, formerly of the UT-Austin's Nuclear and Radiation Engineering Department, was a foundation for the logic programming of the software package.[1] The software package is capable of applying MAUA in order to compute PR values for NFC facilities including mining and milling, conversion, enrichment, fuel fabrication, reactors, reprocessing and permanent storage. The overall goal of the NAT software package is to provide a GUI for the application of a quantitative assessment method for PR values.

This article will briefly present quantitative assessment methodologies and their application in assessing the PR of NFC facilities. Thereafter, the NAT software package will be discussed in full as well as its contribution to the improvement cycle of quantitative assessment methodologies for calculation of PR values of NFC facilities.

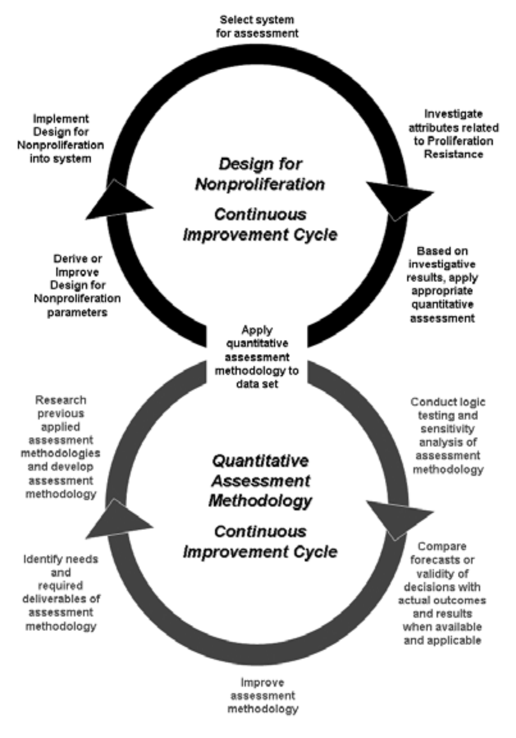
Introduction

The continuous need for the improvement of safeguard activities, both by the International Atomic Energy Agency (IAEA) and individual states, is one of the reasons for development of methods to evaluate the nuclear fuel cycle (NFC) facilities' characteristics in relation to their proliferation resistance. As alluded to by the authors of "Nonproliferation Criteria for Nuclear Fuel Cycle Facilities," the evaluation of criteria related to the proliferation resistances of the nuclear fuel cycle remains murky. "There remain numerous discrepancies amongst those within the nuclear community as to what criteria should be used in attempting to evaluate the nuclear fuel cycle."[4] The difficulty in assessing the large amount of technical details of NFC facilities necessitates not only qualitative methods to assess areas of improvement, but also quantitative methods. However, the challenge of defining attributes is paralleled with the selection of the optimal method of available quantitative assessment methods, as there are numerous methods available for application. R. A. Krawkoski in "Review of Approaches for Quantitative Assessment of the Risks of and Resistance to Nuclear Proliferation from the Civilian Nuclear Fuel Cycle" also recognized the complexity of defining proliferation resistance and those attributes that encompass it. "Of the four 'cardinal issues' defining the public debate on nuclear energy (proliferation, waste, economics, safety), proliferation is by far the most difficult to describe quantitatively."[5]

Quantitative Assessment Methodologies

Quantitative assessment methodologies aid in investigating complex systems and assigning quantitative values in order to facilitate decision making. Quantitative assessment methodologies used in a non-nuclear context include examples such as assigning values related to stocks to indicate whether it is appropriate to buy or sell them or assigning safety factors to automobiles. Inside the nuclear community, the strength of quantitative assessment methodologies is the decomposition of complex systems into manageable subcharacteristics. The pursuit of the "perfect methodology" facilitates a constant dialog about the characteristics of design and application of safeguards and respective technologies. The dialog facilitated could be considered as important as the developed and applied methodology itself. Moving in parallel with the continuous cycle of improvement of quantitative assessment methodologies is the cycle of improvement of design parameters that impact the NFC facilities. These parameters, or Design for Nonproliferation parameters, can be defined as all those aspects that affect the proliferation resistance to diversion of special nuclear materials (i.e., implementation of safeguards or the redesign of seals for spent fuel containers). Figure 1 represents the two cycles of improvement.

Figure 1. Improvement cycles of quantitative assessment methodology and design for nonproliferation



Two publications, "Quantifying Relative Proliferation Risks from Nuclear Fuel Cycles," published in 1986 and "Review of Approaches for Quantitative Assessment of the Risks of and Resistance to Nuclear Proliferation from the Civilian Nuclear Fuel Cycle," published in 2001, explore the available methodologies of quantitatively assessing Proliferation Resistance.[8,5] These publications briefly discuss the application of these methodologies as well as the relevant studies published using these methodologies. Of the numerous types discussed in the publications, an emphasis was placed on the following five:

- Expert Group Delphi
- Comparative Value Measure
- Probabilistic Risk Analysis
- Risk/Consequence Analysis
- Multi-Attribute Utility Analysis

Multi-Attribute Utility Analysis

In 2003, the University of Texas at Austin (UT-Austin) pursued the development of one of the aforementioned quantitative assessment methodologies for PR values, the Multi-Attribute Utility Analysis (MAUA) by William Charlton. MAUA is a tool for making complex decisions based upon attributing numerical values to all options. "Most complex programs involve multiple objectives. Thus, analytical work on such problems requires that one obtain an objective function, involving multiple measures of effectiveness (attributes) to indicate the degrees to which their objectives are met."[3] The methodology begins by selecting a number of attributes, *i*, for a number of different options, *j*. The attributes are translated into numerical values using utility functions, *U(x)*. The attributes have a weighting factor assigned to them via the Expert Group Delphi method, and the outcome of the utility functions and the weighting factors are manipulated for a final numerical value that can be compared for all *j* options. MAUA has been applied to provide decision-makers information in a variety of different situations including "structuring corporate objectives, examining operation policies of fire departments, allocating school-system funds, evaluating time-sharing systems, citing nuclear power facilities, treating medical problems such as cleft lip and palate and so forth."[3]

Table 1. Measures of interest in various publications regarding proliferation resistance of nuclear fuel cycle facilities

(Ioannis A. Papazoglou 1978; P. Silvennoinen 1986; Krakowski 1999)	(Donald Close 1995)	(William S. Charlton 2003)
Minimum development time	Time of processing	Type of accounting system
Inherent technological difficulty related to nuclear weapons fabrication	Safeguards/physical protection	Attractiveness level
Inherent technological difficulty related to materials processing	Technical difficulty of processing	Handling requirements
Warning period	Physical access	Accessibility
Costs	Physical form	Concentration
	Self-protection aspects of the material (i.e., radioactivity)	
	Financial and technical infrastructure	

The application of the Operations Research technique of MAUA to Proliferation Resistance quantification can be found in publications as early as 1978.[6] Thereafter, others have also pursued the application of MAUA for quantifying PR of NFC facilities.[8] Although attributes are translated into numerical values, the methodologies are still biased by the subjective interpretation of the translation. The advantage of applying methodologies is a consistent method of comparison between options. Table 1 compares the measures of interest as presented by the respective authors and illustrates the subjective nature of MAUA methodologies. These measures of interest are translated into numerical values via utility functions.

The goal of the MAUA algorithm is to create a proliferation resistance (PR) value. The MAUA algorithm used at UT-Austin creates a PR value by evaluating and normalizing fifteen different factors related to PR using utility functions[1] (Equation 1). Each of the fifteen different factors (Table 2) are then multiplied by a weighting factor and summed to create a single PR value, ranging from 0 to 1, a value of one indicating the highest level of PR. The weighting factors were determined by expert opinion (Equation 1).

$$PR = \sum_{i=1}^{15} u_i w_i \tag{1}$$

Equation 1. PR value calculation (Charlton, William, and C. Gariazzo. 2003)

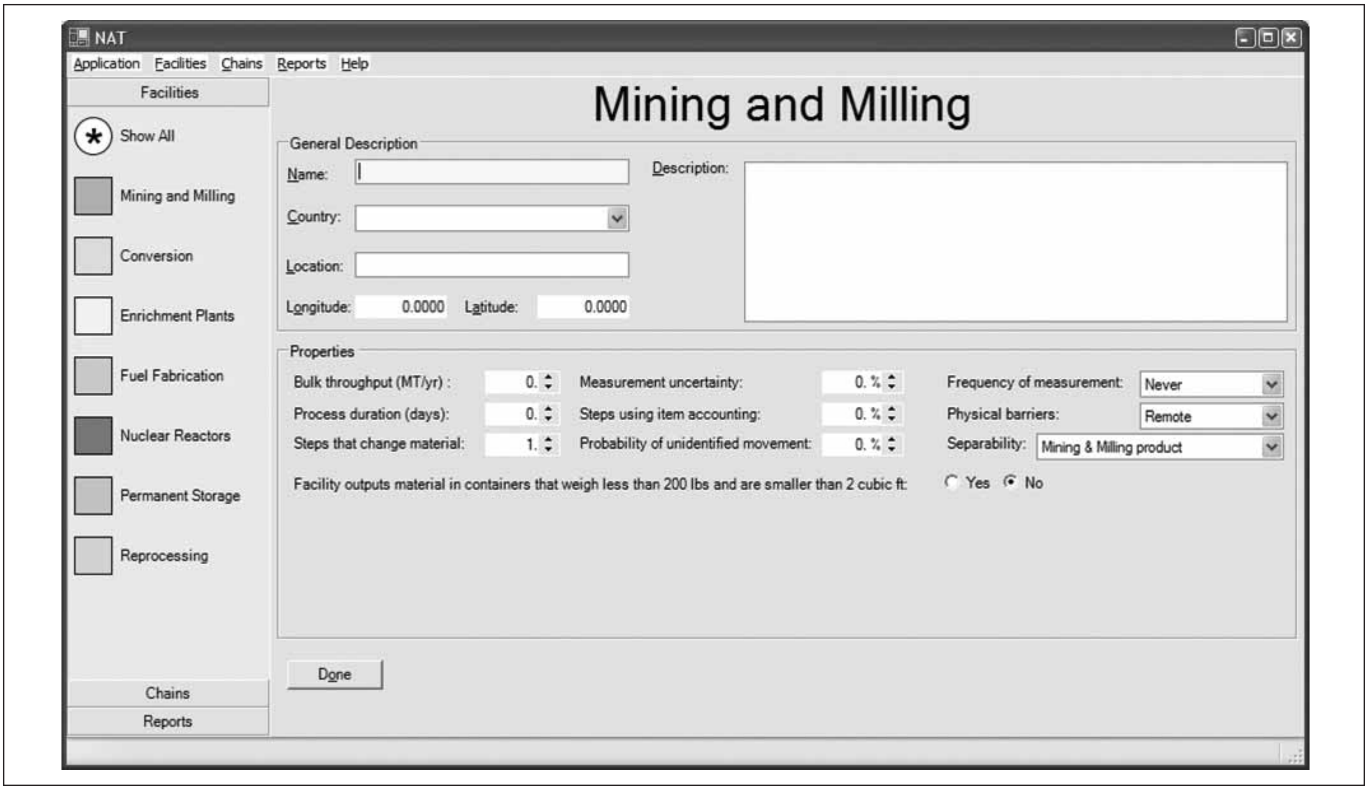
NAT Software Package

Facilities

The NAT software graphical user interface (GUI) is divided into two main sections: Facilities and Chains. The NAT software package begins by prompting the user for specific facility information as required for the MAUA algorithm. Seven facilities are available for analysis in the Facilities' section including milling and mining, conversion, enrichment, fuel fabrication, reactor, reprocessing, and permanent storage. Each of the seven different facilities has a unique screen for data input. (See figures 2 and 3 for examples of two facility data input screens.) After information has been entered into the NAT software package, the PR value is computed. PR values for reactors, reprocessing, and permanent storage facilities require additional computations performed by the ORIGEN 2.2 code, with which the NAT software package interfaces.

ORIGEN 2.2 is a point-depletion and radioactive-decay computer code developed by Oak Ridge National Laboratory. The NAT software uses ORIGEN 2.2 to calculate the nuclide composition and characteristics of materials contained after irradiation and decay that would otherwise be difficult to analyze. Specifically, ORIGEN 2.2 is used in six utility function calculations for the reactor, reprocessing, and permanent storage facilities. Information derived from ORIGEN 2.2 and used in PR calculations include (a) quantity in grams of the elements americium, plutonium, and

Figure 2. Mining and milling facility data input screen contained in NAT software package



Mining and Milling

General Description

Name:

Country:

Location:

Longitude: 0.0000 Latitude: 0.0000

Description:

Properties

Bulk throughput (MT/yr) : 0.

Process duration (days): 0.

Steps that change material: 1.

Measurement uncertainty: 0. %

Steps using item accounting: 0. %

Probability of unidentified movement: 0. %

Frequency of measurement: Never

Physical barriers: Remote

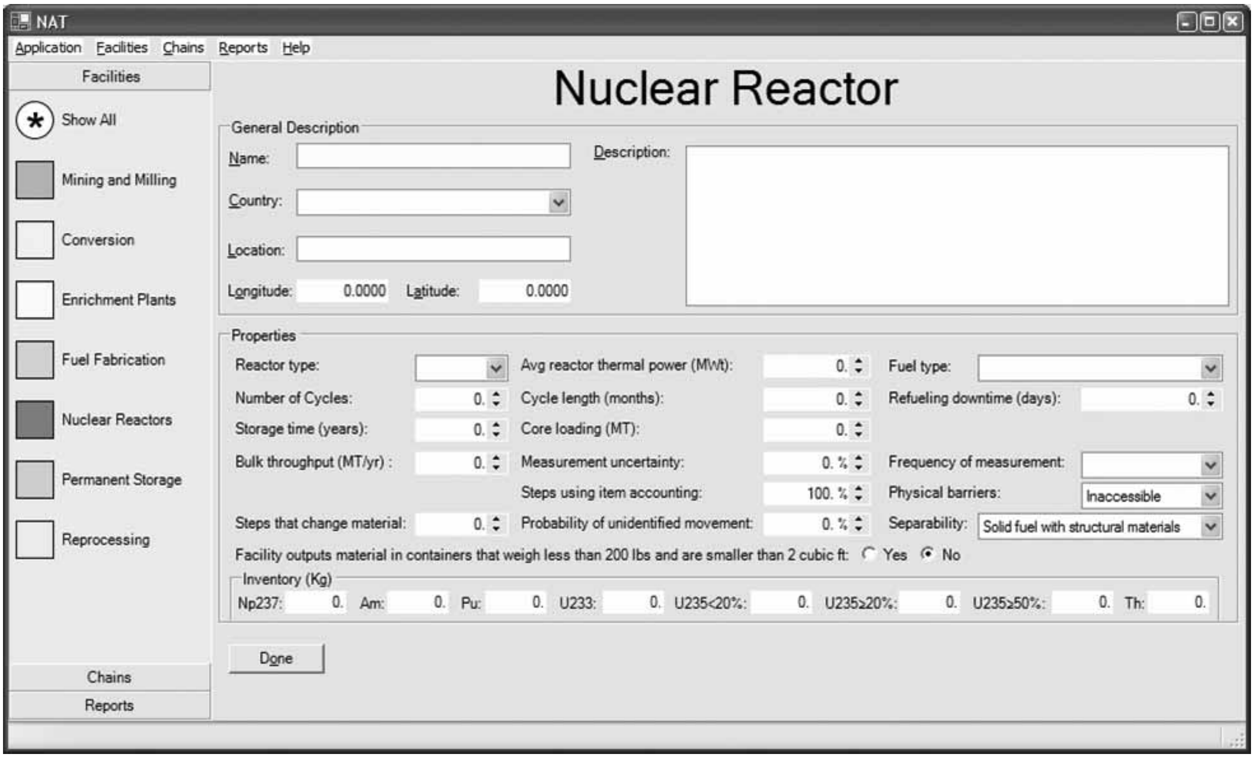
Separability: Mining & Milling product

Facility outputs material in containers that weigh less than 200 lbs and are smaller than 2 cubic ft: ○ Yes ● No

Table 2. Fifteen attributes used in MAUA application to PR quantification by UT-Austin (Gariazzo 2003)

Measure	(i)	Attribute	Weights
Attractiveness Level	1	DOE Attractiveness Level (IB through IVE)	0.10
	2	Heating rate from Pu in material [Watts]	0.05
	3	Weight fraction of even Pu isotopes	0.06
Concentration	4	Concentration [SQs/MT]	0.10
Handling Requirements	5	Radiation dose rates [rem/hr at distance of 1 meter]	0.08
	6	Size/weight (>200 lbs or >2ft^3)	0.06
Type of Accounting System	7	Probability of unidentified movement of material (surveillance)	0.06
	8	Frequency of measurement	0.08
	9	Measurement uncertainty [SQs per year]	0.09
	10	Separability	0.03
	11	Number of processing steps that change material form	0.04
	12	% of processing steps that use item accounting	0.05
Accessibility	13	Physical barriers	0.10
	14	Inventory [SQs]	0.04
	15	Fuel load type (batch or continuous reload)	0.06

Figure 3. Reactor facility data input screen contained in NAT software package



Nuclear Reactor

General Description

Name:

Country:

Location:

Description:

Longitude: 0.0000 Latitude: 0.0000

Properties

Reactor type:

Avg reactor thermal power (MWt): 0.

Fuel type:

Number of Cycles: 0.

Cycle length (months): 0.

Refueling downtime (days): 0.

Storage time (years): 0.

Core loading (MT): 0.

Bulk throughput (MT/yr) : 0.

Measurement uncertainty: 0. %

Frequency of measurement:

Steps using item accounting: 100. %

Physical barriers: Inaccessible

Steps that change material: 0.

Probability of unidentified movement: 0. %

Separability: Solid fuel with structural materials

Facility outputs material in containers that weigh less than 200 lbs and are smaller than 2 cubic ft: ○ Yes ● No

Inventory (Kg)

Np237: 0. Am: 0. Pu: 0. U233: 0. U235<20%: 0. U235≥20%: 0. U235≥50%: 0. Th: 0.

Figure 2. Mining and milling facility screen with depiction of NFC chain in the NAT software package

Chain: test chain b / Argentina

Mining & Milling

Name: San Rafael Mining & Milling

Country: Argentina

Location: 240 km from Mendoza City

Latitude: -32.8000 Longitude: -68.8000

Description: uranium mining

Proliferation Resistance: N/A

Bulk throughput (MT/yr): 25000.

Process duration (days): 10.

Steps that change material: 1.

Measurement uncertainty: 75. %

Steps using item accounting: 10. %

Probability of unidentified movement: 50. %

Frequency of measurement: Quarterly

Physical barriers: Remote

Separability: Mining & Milling product

Facility outputs material in containers that weigh less than 200 lbs and are smaller than 2 cubic ft: ○ Yes ● No

Output facility type: Conversion Facility

Output facility name:

Output capacity: 100. %

Name	Type	Output Capacity
Pilcaniyeu-1	Conversion	100%

Facilities within Active Chains cannot be Archived.

uranium, (b) the quantity of grams of the isotopes Np^{237}, Pu^{238}, Pu^{239}, Pu^{240}, Pu^{242}, Th^{232}, U^{233}, U^{235}, U^{238}, (c) heating rate from plutonium in watts, and (d) radioactivity in curies from the actinides and fission products.

Chains

Chains are created as the user selects facilities that represent the material flow through a NFC chain. Users are allowed to begin the chain at any facility type and include as many facilities as desired within the framework of the pre-defined chain logic. The pre-defined chain logic was designed to model realistically the material movement in the NFC and is encoded within the NAT software package. A chain may depict a simple linear mass flow or a complex branched chain. Figure 4 depicts a view from the chain screen in which a mining and milling facility's attributes are viewed simultaneously with the "chain window" at the bottom of the screen. The "chain window" contains a linear flow of a theoretical NFC chain in South America. A user may navigate between the different facilities of the chain by clicking on the desired facility within the "chain window" in the lower portion of the screen.

After the required facility data have been entered, the data and results can be displayed by a variety of different reports. The NAT software package is capable of producing reports specific to individual facilities and those of the entire NFC chain: facility reports and chain reports, respectively. Table 3 contains a list of these reports along with descriptions of what is contained therein. An example of the PR versus time graph is depicted in Figure 5, representing the PR values of the same NFC in Figure 4. On the x-axis of the PR versus time graph is the time the material spends within the applicable facility, while the y-axis represents the PR value of that facility. The facilities in the PR versus time graph are the respective NFC chains created by the user within the chains section of the software. This graph provides a visual representation of the PR value of the NFC chain to the user and can be copied as an image for further applications by the user.

Table 3. Available reports within NAT software package

Report Type	Report Name	Description
Facility	Input Values	Facility-specific fields and their entered data (useful for data gathering)
	Utility Functions	Utility function values and their respective weights with resulting facility-specific PR value
	Combined Report	Combined input value report and utility function report with resulting facility-specific PR value
Chain	Summary Report	Three-part chain report including (1) pictorial depiction of NFC chain, (2) PR values and additional pertinent fields of all facilities contained within NFC chain and (3) PR versus time graph
	Process Flow Report	Three-part chain report including (1) pictorial depiction of NFC chain, (2) combined reports for all facilities within the NFC chain and (3) PR versus time graph
	PR versus Time Graph	Horizontal bar graph representing each facility over time (x-axis time) and PR value (y-axis) of facility

Integration of ORIGEN 2.2 Code with NAT Software Package

As mentioned previously, the NAT software package utilizes ORIGEN 2.2 to calculate some utility functions for material characteristics that would otherwise be difficult to compute. "ORIGEN 2 is a versatile point-depletion and radioactive-decay computer code for use in simulating NFCs and calculating the nuclide composition and characteristics of materials contained therein."[2] Specifically, ORIGEN 2.2 is used in six utility function calculations for the reactor, reprocessing, and permanent storage facilities. The information used from the resulting ORIGEN 2.2 output decks for the utility function calculations are listed in Table 4.

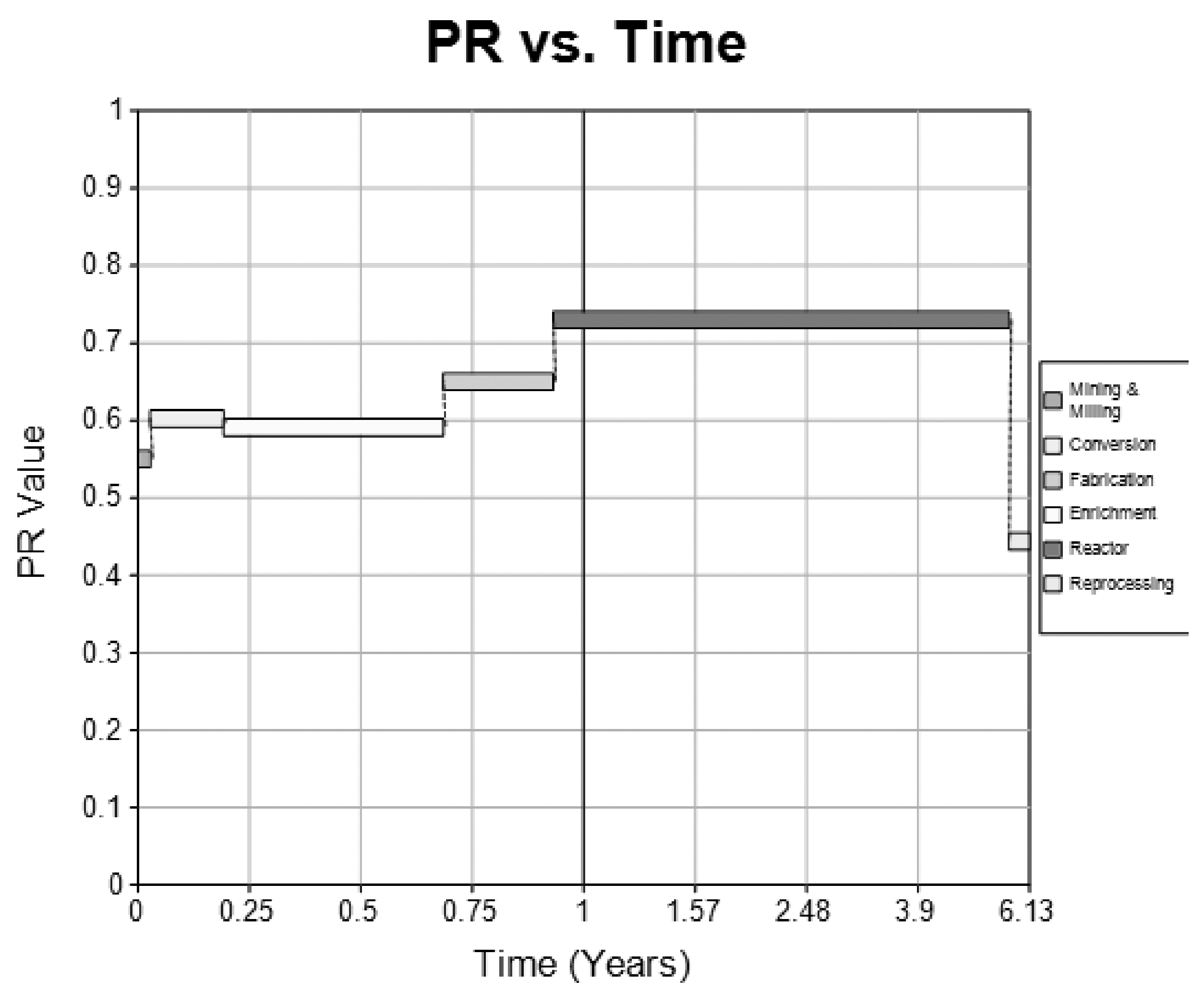
The logic programming created for the integration of ORIGEN 2.2 into the NAT software allows for the user to gain the advantage of using the ORIGEN 2.2 code while not having to become knowledgeable in its execution. In addition, the logic developed for the NAT software package provides a rapid execution and minimization of output data.

The NAT software package uses Microsoft Access 2003, object-oriented programming techniques, and is written in Visual Basic.NET (VB.NET) version 2003. NAT software package version 0.9.6 is now complete and released, including a user's guide and accompanying scientific manual. ORIGEN 2.2 is not included in the package, but must be installed on the same computer for NAT to operate properly. ORIGEN 2.2 can be obtained by request through the Radiation Safety Information Computational Center (RSICC). The NAT software package can be obtained by contacting the Oak Ridge National Laboratory's International Safeguards Group.

Table 4. ORIGEN 2.2 fields used in utility functions

Utility Functions	Composition (*Grams*)												Heating Rate from Pu (*Watts*)	Radioactivity (*Ci*, Actinides and Fission Products)
	U	U^{233}	U^{235}	Pu	Pu^{238}	Pu^{239}	Pu^{240}	Pu^{241}	Pu^{242}	Pu^{232}	Pu^{237}	Am		
DOE Attractiveness Level		✓	✓	✓										
Heating Rate from Pu													✓	
Weight Fraction of Even Pu Isotopes					✓	✓	✓	✓	✓					
Concentration of Significant Quantities	✓		✓	✓						✓	✓	✓		
Radiation Dose Rate														✓
Measurement Uncertainty	✓		✓	✓						✓	✓	✓		

Figure 5. Proliferation resistance value versus time graph generated by the NAT software package



Conclusion

With the continued use of nuclear power throughout the world, safeguards and security of special nuclear materials is a continued concern. Quantitative assessment methods for determining PR values aid decision makers and those interested in continual improvement of safeguards and security for NFC facilities. These methods have been in development for more than twenty years and have become more data intensive and complex over time.[1,8] A development in the area of quantitative assessment methods for determining PR values is the NAT software package, which provides a graphical user interface. Advantages of a GUI interface for calculation of PR values includes reducing the number of possibilities for computational errors in the calculation of PR values due to human error. Secondly, the GUI produces an efficient and standardized manner in which to store, collect, and share data associated with fuel cycle facilities and proliferation resistance. Lastly, a GUI provides the opportunity to integrate other complex codes, such as ORIGEN 2.2, to formulate information on material characteristics. Included in this NAT software package is the ability to enter facility information and build NFC chains. The computations include the fifteen utility functions as well as the PR value for each facility. ORIGEN 2.2 is interfaced with the NAT software package, providing a tool to calculate material-specific information after irradiation and decay. Additionally, several reports and illustrations are available within the software package to display results.

The NAT software package was developed in cooperation with Oak Ridge National Laboratory. It is to be utilized as a decision-making tool in investigating areas of improvement in safeguards and security of NFC facilities around the world.

References

1. Charlton, W., and C. Gariazzo. 2003. Development of a Proliferation Resistance Methodology for Assessing Safeguard Effects in Fuel Cycles. *Proceedings of the 43rd Annual Meeting of the Institute of Nuclear Materials Management.*
2. Gariazzo, C. 2003. *Development of a Methodology for the Assessment of International Safeguards on the Commercial Nuclear Fuel Cycles of Argentina and Brazil.* Master of Science Thesis: University of Texas in Austin.
3. Keeney, R. L. 1993. *Decisions with Multiple Objectives.* New York: Cambridge University Press.
4. Kiriyama, E. 2000. Nonproliferation Criteria for Nuclear Fuel Cycle Options, *Progress in Nuclear Energy* 37, 71-76.
5. Krakowski, R. A. 2001. *Review of Approaches for Quantitative Assessment of the Risks of and Resistance to Nuclear Proliferation from the Civilian Nuclear Fuel Cycle*, Los Alamos: Los Alamos National Laboratory, 1-45.
6. Papazoglou, I. A. 1978. *A Methodology for the Assessment of the Proliferation Resistance of Nuclear Power Systems*, Cambridge, Massachusetts: MIT Energy Laboratory. 1-128.
7. Pratt, V. 2005. *Development of Logic for Nonproliferation Assessment Tool Software Package.* Master of Science Thesis: University of Texas in Austin.
8. Silvennoinen, P. 1986. Quantifying Relative Proliferation Risks from Nuclear Fuel Cycles, *Progress in Nuclear Energy* 17, 231-243.
9. Silvennoinen, P. 2004. An Approach to Quantitative Assessment of Relative Proliferation Risks from Nuclear Fuel Cycles, *Journal of the Operational Research Society* 32, 457-466.

Non-Destructive Assay of Nuclide Composition in Spent Fuel Assemblies from a Research Reactor by Repeat Irradiation and Gamma-Spectrometric Measurement

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Abstract

This paper presents a method for the experimental determination of ^{235}U, ^{236}U, ^{237}Np, and ^{238}U content in spent fuel of a research reactor. The method is based on a repeat short-term irradiation of the spent fuel assembly followed by measurement of gamma-radiation spectra. The paper describes the experiments carried out with spent fuel assemblies from the research reactor IRT-MEPhI. The results obtained in the measurements and an analysis of experimental errors are presented.

Based on the results obtained it is concluded that the proposed method is superior to other non-destructive methodologies both in accuracy and the scope of information available about the nuclide composition of spent fuel.

Introduction

Research reactors represent the most widely distributed type of nuclear reactors. These reactors use a highly enriched uranium fuel, and a significant fraction of fissionable isotope remains in spent fuel. Operation of the research reactors is going on now all over the world, and the number of spent fuel assemblies (FA) grows both in Russia and abroad.

The methods for control of fuel burn-up and residual amounts of fissionable nuclides in spent FA developed for power reactors[1] are poorly adapted for conditions of research reactor operations. Frequent power variations and lengthy shutdowns in the reactor operation affect the build-up of nuclides that emit gamma-rays and neutron radiation. These effects complicate interpretation of experimental data. So, there is an urgent necessity for developing a new control methodology suitable for sufficiently accurate determination of fuel burn-up and uranium isotopic composition in spent FA discharged from research reactors. The present experimental results can be used as a basis for verification and validation of the computer codes used to determine such composition.

The main purpose of the present work is an investigation of the possibility of obtaining experimental information about the content of actinides in spent FA discharged from the research reactor IRT-MEPhI by means of additional neutron irradiation followed by gamma-spectrometric measurements. In such a case, the research reactor itself serves as a neutron source for FA irradiation, and fresh FA may be used as reference materials because uranium content in fresh FA is known with high precision. An important advantage of the proposed methodology is its independence of FA irradiation history. Such history is usually required for decoding the measurement results on fuel burn-up in the reactors operating in a regime with frequent power variations.

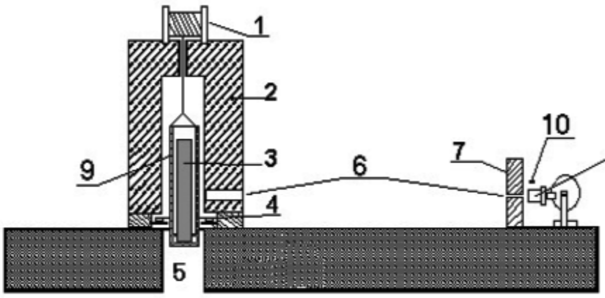
IRT-MEPhI is a pool-type research reactor of 2.5 MW power.[2] Similar reactors are under operation now in Russia and some other countries. Traditional loading of the IRT-MEPhI core consists of nine six-tube FA and seven eight-tube FA with initial uranium enrichment of 90 percent ^{235}U, and with different values of fuel burn-up. The IRT-3M FA consists of eight concentric tubular fuel elements (seven fuel elements of square cross-section and one central fuel element of circular cross-section). Each fuel element represents a three-layer tube consisting of uranium-aluminum meat (0.4 mm thick) and two aluminum claddings (0.5 mm thick each). The mass of ^{235}U in one FA is about 300 g; the length of the active, fuel-containing part is equal to 580±20 mm. The design of the six-tube FA differs from that of eight-tube FA by the absence of the two central fuel elements. It is noteworthy that the FA of the IRT-MEPhI is almost transparent to high-energy gamma-radiation.

Spent fuel assemblies with average fuel burn-up of about 50 percent are stored in the cooling pool before transportation for reprocessing, and they may be used for experimental studies. The experiments were carried out with five eight-tube FA (three spent FA, two fresh FA) and one fresh six-tube FA.

The fuel assemblies were irradiated at the periphery of the reactor core, in the cell where a beryllium reflector block was removed and the FA to be studied was inserted in its place. The thermal neutron flux was about $2{\cdot}10^{13}$ cm^{-2} s^{-1} in the cell. The irradiation lasted for three days.

To measure the neutron fluence in the FA for the irradiation time, aluminum wire-monitors (diameter–0.5 mm) were inserted in a central tube to the full length of the tube. One wire-monitor contained about 3 percent copper; another, about 0.1 percent cobalt. Uniformity of copper and cobalt distribution along the

Figure 1. Layout of the measuring device



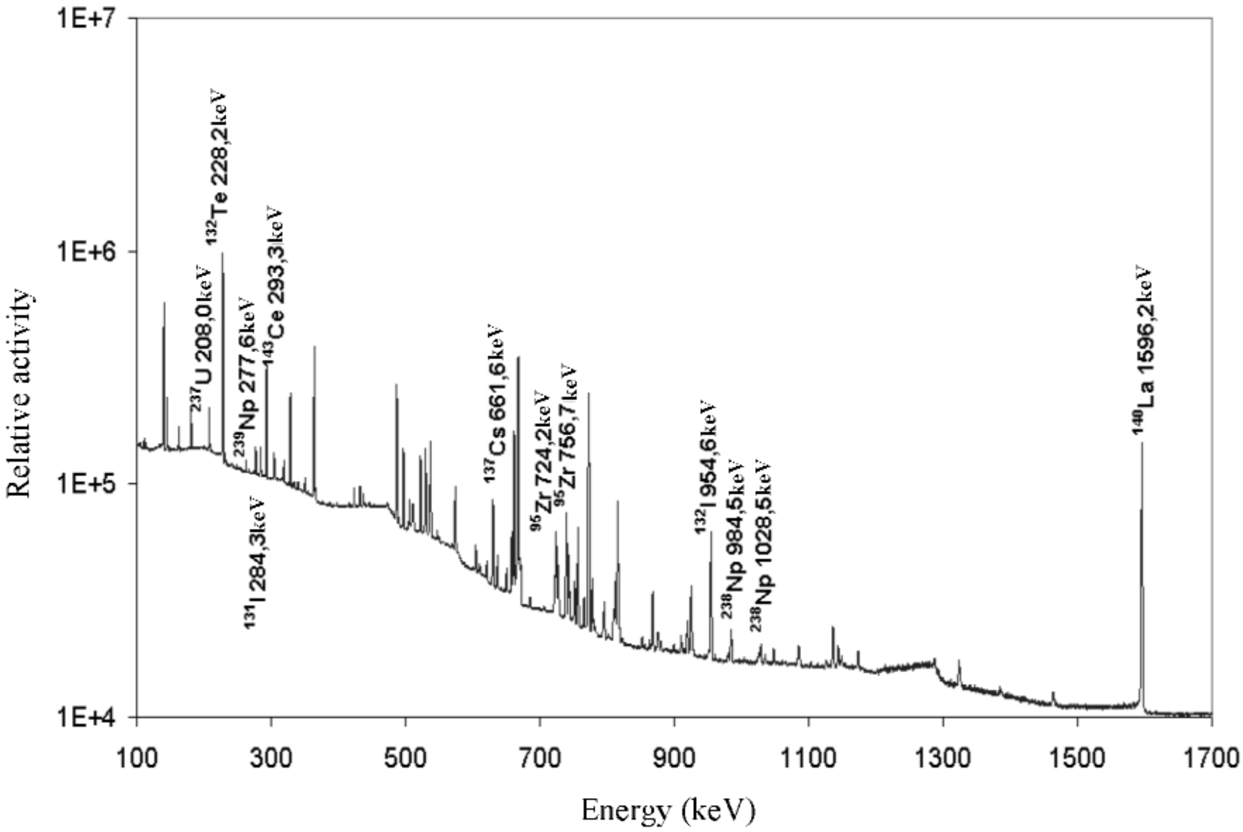
1 – winch for hoisting of FA; 2 – refueling container; 3 – FA; 4 – device for FA rotation; 5 – refueling channel; 6 – collimation holes; 7 – lead shielding of detector; 8 – Ge-detector; 9 – bucket of refueling container; 10 – Co^{57} source for correction of miscounts

wire length was confirmed by dedicated experiments. After irradiation, the wires were withdrawn, and induced activities of ^{64}Cu and ^{60}Co were measured. The results obtained in FA scanning were compared with indications of the wire-monitors that allowed us to account for some differences in the neutron fluxes during the irradiation of fresh and spent FA, and in the reactor power levels for different experiments.

The activity of the spent FA reached several tens of thousands of curies. After repeat irradiation, this activity was further increased. Thus dedicated equipment was required for handling with irradiated FA and for conduction of these experiments (Figure 1).

The experiments were carried out in the IRT-MEPhI reactor hall. The irradiated FA was placed into a thick-walled lead container with a collimation hole by means of which a detector was able to measure gamma-radiation from certain parts of the FA surface. All eight fuel elements of the FA gave their own contribution to this gamma-radiation. The dedicated electro-mechanical system was used for azimuth and vertical movements

Figure 2. Gamma-radiation spectrum from spent FA after short-term repeat irradiation in the reactor core



of the FA. The axial position of the FA with respect to the collimation hole was stringently fixed while an uncertainty in azimuth position of FA was compensated by continuous rotation during the measurement. The coaxial germanium detector connected to a personal computer was used for the gamma-spectrometric measurements. The measuring system was additionally shielded in order to attenuate an external background of scattered radiation. An optimal counting rate was selected by changing diameter of the collimation hole. Absorbing cadmium filters were used to reduce the counting rate in the low energy range. Pulse pileup in the measuring system was accounted for by use of a reference source.

Peaks of three long-lived nuclides ^{134}Cs, ^{137}Cs (fission products) and ^{154}Eu (product of repeated neutron capture) were observed in the gamma-spectra of the spent FA after a three-year cooling time. The experiments demonstrated that, three days after the repeat irradiation, many peaks created by short-lived fission products (Figure 2) may be observed in the gamma-spectra. These peaks, however, do not impede the measurements of the intensity of the radiation emitted by some actinides (^{236}U, ^{237}Np, ^{238}U). Evidently, the intensity of the peaks from fission products defines the content of fissionable isotopes in the fuel while the intensity of the peaks from actinides contains information about the content of such nuclides in the fuel.

The content of ^{238}U in fresh fuel is below 10 percent. Therefore, the plutonium contribution to the fission reaction rate is very small even for FA with high fuel burn-up. Analysis of gamma-spectra from FA after repeat irradiation demonstrated that the peak of ^{140}La (energy - 1,596 keV) is the most suitable for measurements of ^{235}U content. Comparison of ^{140}La radiation intensities from spent and fresh FA (where ^{235}U content is known with high precision) makes it possible to determine the residual amount of this isotope in spent FA.

Preliminary measurements of 185.7 keV radiation emitted by ^{235}U from fresh FA have confirmed available data on the uniformity of the fuel distribution over the full length of the active part of the FA, with the exception of the most distant regions.

The measurements of residual ^{235}U content were begun ten days after irradiation and lasted five days. For this time interval five series of experimental studies were carried out including measurements at seventeen axial positions. The results obtained allow us to calculate the axial distribution of the ^{235}U content and the full mass of residual ^{235}U in the FA.

Determination of Residual ^{235}U Mass in FA

The mass of ^{235}U in the spent FA was calculated from the following formula:

$$M_{5,\text{в}} = \frac{M_{5,c} \sum_i \beta_i \left(\frac{A_{La,\text{в}}}{A_{Cu,\text{в}}}\right)_i \Delta z_i}{\sum_i \left(\frac{A_{La,c}}{A_{Cu,c}}\right)_i \Delta z_i} \qquad (1)$$

where: $M_{5,c}$ is the mass of ^{235}U in fresh FA; Δz_i is the the portion of the FA length over which the measured activities of ^{140}La and ^{64}Cu were considered constant; $(A_{La,\text{в}}/A_{Cu,\text{в}})_i$ is the ratio between the measured saturated activities of ^{140}La and copper indicators in i-region of spent FA; $(A_{La,c}/A_{Cu,c})_i$ is the the same value for fresh FA; βi is the the calculated correction factor that accounts for spectral differences and differences in attenuation of the neutron flux in i-region of fresh FA and spent FA.

At Russian research reactors, fuel burn-up (B) is defined as the fraction of ^{235}U nuclei that disappears in fission and capture reactions. Then, fuel burn-up may be calculated using the following formula:

$$B=(1-M_{5,\text{в}}/M_{5,0})\cdot 100\%, \qquad (2)$$

where $M_{5,0}$ is the initial ^{235}U mass in spent FA.

The axial distributions of the ^{235}U content in fresh and spent FA are presented in Figure 3, together with the axial distribution of fuel burn-up in spent FA and the axial distribution of the thermal neutron flux, including the regions outside the active parts of the FA.

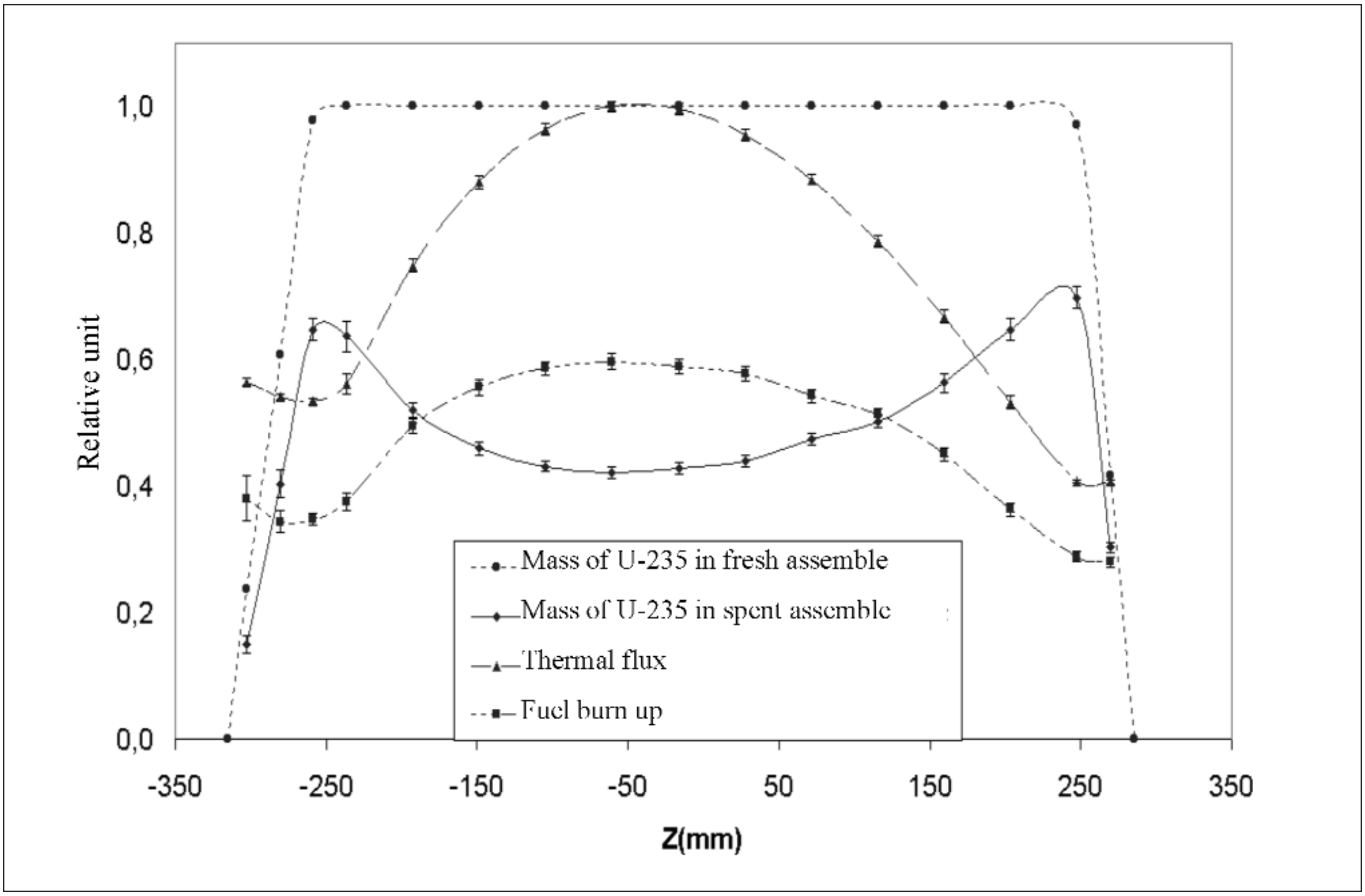
It can be seen from these distributions that, as should be anticipated, the uranium concentration in the central part of a fresh FA is almost constant while in a spent FA the concentration of ^{235}U is significantly lower than that in fresh FA, and its axial distribution is non-uniform. Fuel burn-up in the central part is higher than that at the FA edges. A slight increase of fuel burn-up in the most distant FA regions may be caused by a reflected thermal neutron flux at the core boundary. The asymmetrical axial distribution of fuel burn-up may be explained by the effects of control rods inserted from the top into the reactor core.

The error in the determination of ^{235}U mass in spent FA is mainly defined by the errors in the measured activities of ^{140}La and ^{64}Cu, and by the calculated correction factors. The contributions given by errors of all the values in formula (1) to the total error of the final result are shown in Table 1.

Table 1. Error components in determination of ^{235}U mass and fuel burn-up

Measured and Calculated Parameters	$M_{5,0}$	A_{La}	A_{Cu}	β_i	$M_{5\,\text{в}}$	B
Relative Errors (1α)	0.03 percent	0.3-0.6 percent	0.3-0.4 percent	0.5 percent	(1,0-1,4) percent	(1,0-1,4) percent

Figure 3. Axial distributions of 235U content, fuel burnup, and thermal neutron flux in FA



The fuel burn-up averaged over FA was calculated from the total residual uranium mass and the known value of the initial uranium mass in the FA. Appropriate experimental data are presented in Table 2.

Table 2. Determination of residual ^{235}U mass and fuel burn-up

FA No.	Residual ^{235}U	Fuel Burn-up in FA, percent	
	mass, g	average	maximal
126	153.2±2,2	50.6 ± 0.7	62.0 ± 1,9
127	157.1±2,3	49.5 ± 0.7	61.1 ± 1,8
183	157.2±1,4	47.3 ± 0.4	59.6 ± 1,3

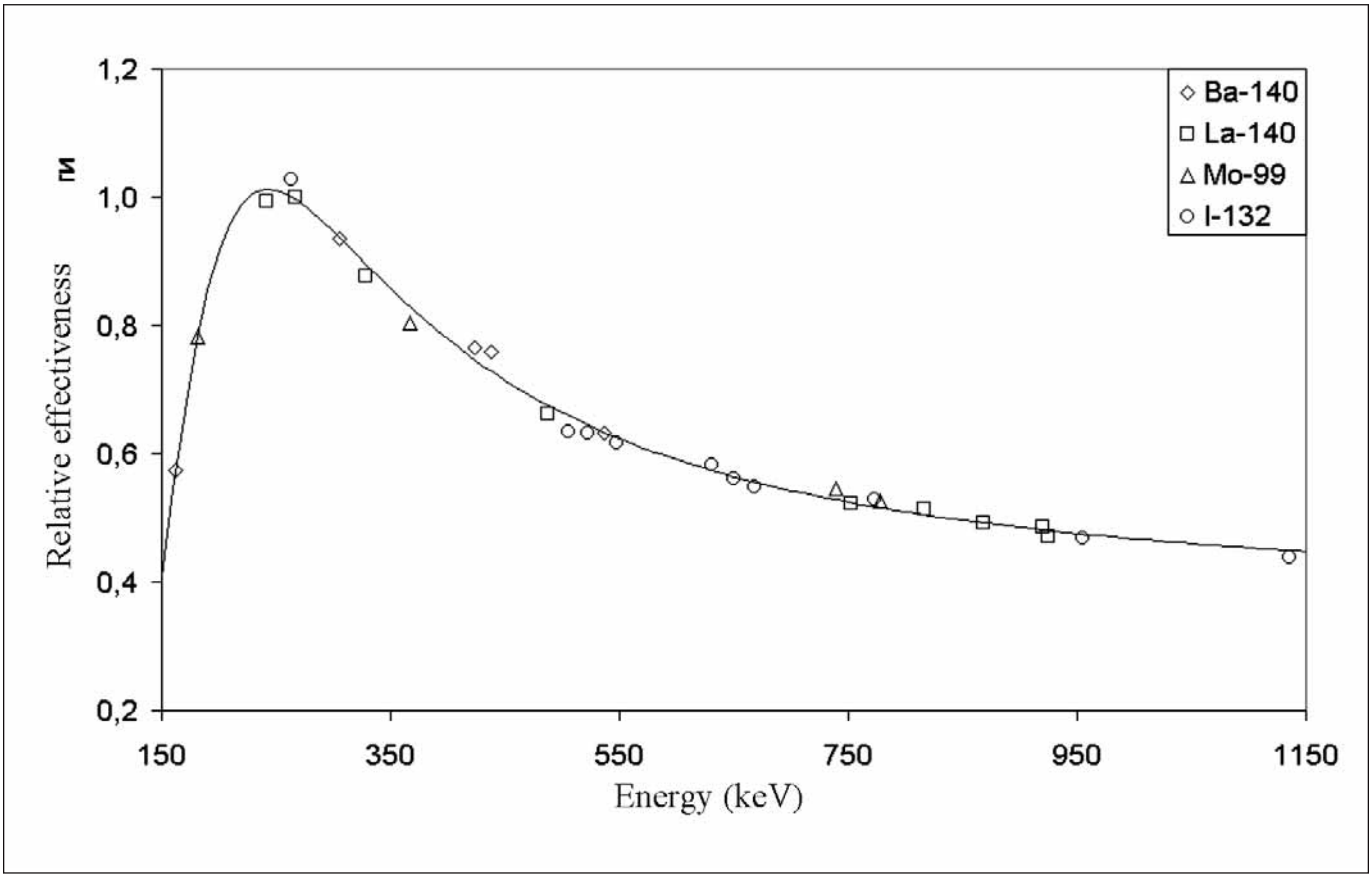
Determination of ^{236}U, ^{237}Np, ^{238}U contents in spent FA

The measurements of the radiation emitted by ^{236}U, ^{237}Np, and ^{238}U were begun three days after irradiation and lasted five days. The measurements lasted from two to eighteen hours. In order to determine the reaction rate ratios ^{236}U(n,γ)/^{235}U(n,La), ^{237}Np(n,γ)/^{235}U(n,La) and ^{238}U(n,γ)/^{235}U(n,La), appropriate fission products were selected for each actinide using the following criteria:

- The fission product is characterized by half-life suitable for measurements (several days).
- Energies of gamma-rays emitted by the fission products do not differ significantly from those of the capture products. This allows one to minimize the corrections for absorption of gamma-rays in the FA and for the efficiency of gamma-ray detection.
- Nuclear data (yield per fission and radiation yield) are known with high precision.

Using these criteria, the following gamma lines of fission products were selected: 228.2 keV of ^{132}Te, 293.3 keV of ^{143}Ce, 284,3 keV of ^{131}I, 954,6 keV of ^{132}I. The nuclear properties required for calculating the final results are presented in Table 3.

Figure 4. Energy dependence of the gamma-radiation detection efficiency



The reaction rate ratios were calculated from the measured saturated activities of these nuclides with application of the following formula:

$$\frac{R_\gamma}{R_f} = \frac{A_\gamma}{A_f} \cdot K \cdot Y_f \quad (3)$$

where: $\frac{A_\gamma}{A_f}$ is the saturated activities ratio of the measured nuclides; Y_f - cumulative yield of fission product; K- is thecorrection factor accounting for difference between detection efficiency of the gamma radiation emitted by the actinide and the fission product.In order to determine the reaction rate ratios, it is necessary to know the correction factor K, which can be found from the energy dependence of the relative gamma-radiation detection efficiency. The relative detection efficiency accounts for absorption of gamma-radiation in the FA, during the radiation transport from the FA to the detector, and for the efficiency of the radiation detection by the detector. To plot such a curve, peaks of four fission products (^{140}Ba, ^{140}La, ^{132}I, ^{99}Mo) were used. The energy ranges where these peaks may be observed are partially overlapped, which allowed us to perform a mutual normalization. The efficiencies were calculated with respect to the detection efficiency

Table 3. Nuclear data for the measured nuclides [3,4]

Nuclide	Half-Life, Days	Energy of Gamma-Rays, keV	Yield of Gamma-Rays, Percent	Yield of Nuclide Per a Fission, Percent
^{237}U	6.75	208.0	21.2 ± 0.3	–
^{132}Te	3.26	228.2	88 ±4	4.25± 0.04
^{239}Np	2.35	228.2 277.6	11.14 ± 0.11 14.44 ± 0.10	–
^{131}I	8.04	284.3	6.1 ± 0.1	2.89 ± 0.03
^{143}Ce	1.38	293.3	42.8 ± 0.5	5.94 ± 0.43
^{132}I	3.26*	954.6	17.6 ± 0.5	4.27 ± 0.04
^{238}Np	2.12	984.5 1028.5	25.19 ± 0.21 18.29 ± 0.24	–

** Half-life of ^{132}I is defined by half-life of the parent nuclide ^{132}Te.*

of gamma-rays with an energy of 266.6 keV (line of ^{140}La). The plotted curve of the relative detection efficiency is shown in Figure 4.

The correction factor calculated from this energy dependence among the chosen pairs of gamma-lines was equal to 5.4 percent with an error of less than 1 percent.

The errors in determination of the reaction rate ratios are shown in Table 4.

Using the measured reaction rate ratios, residual ^{235}U mass (from Table 2), the calculated microscopic cross-sections of neutron capture reactions for ^{236}U, ^{237}Np, ^{238}U and fission reactions for ^{235}U, the amount of these nuclides in the spent FA was determined (see Table 5).

The last row of Table 5 shows the concentration of ^{238}U in FA 183. This concentration was derived from the relative measurements of ^{239}Np activity in fresh and spent FA. The concentrations of ^{238}U obtained by two different methods agreed within experimental error.

As a result of fuel irradiation in the reactor core, ^{235}U is burned while ^{236}U is accumulated in the FA. Since fuel burn-up varies along FA height, one may obtain information about variations of ^{236}U/^{235}U content ratio (Table 6).

Conclusions

The main results obtained in the study are listed below:

- The capabilities of non-destructive analysis were investigated in experimental studies to determine the nuclide composition in spent fuel assemblies discharged from a research reactor. The initial enrichment of fresh uranium fuel was 90 percent ^{235}U. Spent fuel nuclide composition was measured by a methodology that includes an additional, short-term irradiation followed by gamma-spectrometric measurements. The results of such a non-destructive assay yielded information about the residual quantity of fissionable material and about its quality, i.e., about the fraction of ^{236}U (the isotope that cannot be fissioned by thermal neutrons) in the uranium isotopic mixture.

Table 4. Error components in determination of the reaction rate ratios

Measured and calculated parameters, nuclear data	Relative error (1α)
Half-life, time of irradiation, cooling and measurement	< 0.5 percent
Yield of gamma-rays per one decay	2~5 percent
Yield of nuclides per one ^{235}U fission	1~7 percent
Error in determination of peak area	0.1~4 percent
Correction on the relative gamma-radiation detection efficiency	< 1 percent
Total error in the reaction rate ratios	3~6 percent

Table 6. Dependence of ^{236}U/^{235}U ratio on fuel burn-up

FA No.	127	127	127	183
Height, mm	-192,5	-82,5	27,5	27,5
Burn-up, percent	49,7±1,3	59,8±1,8	59,1±1,9	57,8±1,2
^{236}U/^{235}U	0.180±0.010	0.264±0.015	0.253±0.015	0.227±0.012

- The capabilities of the methodology were evaluated to determine fuel burn-up and residual ^{235}U content in the FA of the research reactor IRT-MEPhI. It was found that the repeat irradiation method enables one to determine the fuel burn-up with better accuracy than other experimental methodologies.
- Comparison of the results obtained with permissible values of fuel burn-up in such FA allows one to conclude that the

Table 5. Contents of ^{235}U, ^{236}U, ^{237}Np and ^{238}U in spent FA

FA No.	127	127	127	183
Height, mm	-192.5	-82.5	27.5	27.5
B (percent)	49.7±1.3	59.8±1.8	59.1±1.9	57.8±1.2
^{235}U (g/cm)	2.88±0.07	2.38±0.05	2.40±0.08	2.36±0.05
^{236}U (g/cm)	0.518±0.029	0.628±0.038	0.607±0.037	0.535±0.026
^{237}Np (g/cm)	0.0166±0.0006	0.0219±0.0011	0.0194±0.0013	0.0179±0.0006
^{238}U (g/cm)	0.547±0.018	0.560±0.024	0.562±0.025	0.526±0.015
	–	–	–	0.510±0.064

irradiation time of these FA may be prolonged by several percent.

In the future, we are going to study the possibility of extending the applicability of the additional irradiation methodology to spent FA with lower fuel enrichment. This requires a significant modification of the methodology and can lead to increased errors in the experimental results.

References

1. Reilly, D., N. Ensslin, H. Smith and S. Kreiner. 1991. *Passive Nondestructive Assay of Nuclear Materials.* NUREG/CR-550. LA-UR-90-732.
2. Bat, G. A., A. S. Kochenov, and L. P. Kabanov. 1985. *Research Nuclear Reactors*, Moscow, Energoatomizdat, pp. 203-223
3. JELA-PC Version 2. A PC Program Laor Displaying Data Larom the Joint Evaluated LAile (JELA) Library.
4. National Nuclear Data Center, Brookhaven National Laboratory, Upton, NY 11973-5000. Nuclear Structure & Decay Data (02/18/2004).

Evaluation of Risk for Acts of Terrorism Using Belief and Fuzzy Sets

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Abstract

Risk is a function of the likelihood of an event and the consequence of that event. There is uncertainty associated with estimating risk for an event that may happen in the future. A terrorist act is not a random event; it is an intentional act by a thinking malevolent adversary. Much of the uncertainty in estimating the risk of a terrorist act is epistemic (state of knowledge) instead of aleatory (stochastic); for example, the adversary knows what acts will be attempted, but we as a defender have incomplete knowledge to know those acts with certainty.

To capture the epistemic uncertainty in evaluating the risk from acts of terrorism, we have applied the belief/plausibility measure of uncertainty from the Dempster/Shafer Theory of Evidence.[1,2] Also, to address how we as a defender evaluate the selection of scenarios by an adversary, we have applied approximate reasoning with fuzzy sets. We have developed software in Java to perform these evaluations.

We have applied these techniques to cyber security, and to the security of nuclear materials and nuclear weapons.

This paper summarizes our work for evaluating risk from acts of terrorism using these techniques.

Introduction

First, we develop the equations for evaluating the risk of a terrorist act. Then, we briefly discuss the belief/plausibility measure of uncertainty, and fuzzy sets. Finally, we discuss how risk from potential acts of terrorism can be evaluated using belief/plausibility and fuzzy sets.

A short appendix summarizes the mathematics of the belief/plausibility measure of uncertainty.

Risk of a Terrorist Act

For a terrorist event, the likelihood of the event is taken as the product of (a) the likelihood of an attack and (b) the likelihood that the attack is successful in causing undesired consequences. The likelihood of an attack can be represented as a frequency, f_A, with units of inverse time; the frequency of attack is a quantitative measure of threat.[i] The likelihood that the attack is successful can be represented as a probability, 1- P_E, where P_E is the effectiveness of the security system (the probability that the security system defeats the attack).[ii, iii] The probability of a successful attack is a quantitative measure of vulnerability. Let C represent consequence (e.g., the number of fatalities). P_E is conditional on the attack, and C is conditional on success of the attack.

For a terrorist act, risk is dependent on the scenario. Here, scenario is defined to include the adversary resources, attack plan, and target. Resources include attributes (equipment, weapons, number of attackers) and knowledge (perhaps from insiders). f_A is conditional on the scenario as the likelihood of an attack depends on the adversary perception of the attractiveness of the scenario (including the target). P_E is conditional on the scenario, since the chance of adversary success depends on the adversary resources. C is conditional on the target in the scenario.

One measure of risk is the product of likelihood and consequence. Using this measure of risk, the risk for scenario "i" is:

$$Risk_i = f_{A_i} * (1 - P_{E_i}) * C_i \qquad (1)$$

The total risk can be expressed as the sum of the risk from each scenario:

$$Total\ Risk = \sum_i Risk_i \qquad (2)$$

In practice, Equation 2 is not evaluated due to the essentially unlimited number of possible scenarios; instead Equation 1 is evaluated for a set of scenarios and the scenarios are ranked by decreasing risk.

The product measure of risk does not delineate between high likelihood, low consequence, and low likelihood, high consequence events with similar risk. Another measure of risk is the likelihood of consequence, which provides more information than the product measure.

Let S_i denote scenario "i". The frequency of consequence for S_i will be defined as

$$F_{A_i} \equiv f_{A_i} * (1 - P_{E_i}) \qquad (3)$$

F_{Ai} is the frequency at which consequence C_i occurs. To express risk as likelihood of consequence, we can define the risk for each scenario as a risk triplet:[3]

$$Risk_i = \ < S_i, F_{A_i}, C_i > \tag{4}$$

With this formulation we can distinguish among scenarios that have similar “risk” as calculated using Equation 1, but that have significantly different frequencies and consequences. Total risk is the set of all risk triplets:

$$Total\ Risk = \ \{< S_i, F_{A_i}, C_i > over\ all\ i\} \tag{5}$$

Following this approach we can calculate the “exceedance frequency of consequence” for the collection of scenarios.[3] Define $L_i(c)$ as the likelihood that consequence C exceeds a specific value c given adversary success for scenario S_i.[iv] For a collection of “i” scenarios, the frequency of exceedance of consequence value c is:

$$Freq(c) = \sum_i F_{A_i} * L_i(c) \tag{6}$$

Freq(c) over all c expresses risk as an exceedance frequency of consequence.

Uncertainty

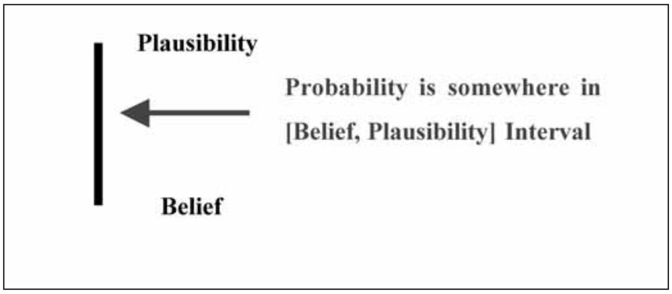
Each variable contributing to risk has uncertainty. To include uncertainty in the evaluation of risk, each variable is treated as a random variable with a likelihood distribution. The likelihood distributions are convoluted under the appropriate algebraic operations used to evaluate risk (for example, the operations in Equation 1 or Equation 6).

Over the last fifty years, mathematicians and logicians have developed measures of uncertainty that are more general than probability, and that specifically address epistemic uncertainty. The references provide details. Appendix A of this paper summarizes the mathematics of the belief/plausibility measure of uncertainty.

The belief/plausibility measure of uncertainty from the Dempster/Shafer Theory of Evidence is an extension of the probability measure of uncertainty that can better capture epistemic uncertainty. Belief/plausibility is a superset of probability and under certain conditions belief and plausibility both become probability. Under other conditions belief/plausibility become necessity/possibility, respectively.[v,2,4] Belief/plausibility addresses a type of uncertainty called ambiguity. The uncertainty associated with predicting an event in the future is ambiguity.

A simple example illustrates the difference between aleatory and epistemic uncertainty, and the use of a belief/plausibility measure. Consider a fair coin, with heads on one side, tails on the other, each side is equally likely. The uncertainty as to the outcome of a toss—heads or tails—is aleatory. The probability of heads is 1/2 and the probability of tails is 1/2. The uncertainty is due to the randomness of the toss. Suppose however that I do not know the coin is fair; the coin could be biased to come up heads, or the coin could even be two-tailed. Now I have epistemic uncertainty; my state of knowledge is insufficient to assign a probability to heads or tails, all I can say is the likelihood of heads (or tails) is somewhere between 0 and 1. To consider epistemic uncertainty as well as aleatory uncertainty, belief/plausibility can be used as the measure of uncertainty. With total ignorance about the coin, the belief that the toss will be heads is 0 and the plausibility that the toss will be heads is 1; similarly, the belief that the toss will be tails is 0 and the plausibility that the toss will be tails is 1. Belief/plausibility form an interval that can be interpreted as giving the lower and upper bound of probability. If I have enough information, both belief and plausibility reduce to a single value, probability. Figure 1 illustrates this concept. Epistemic uncertainty can be reduced with more information. If I toss the coin a few times and a heads and a tails occur, I know the coin is two sided; with more tosses I can evaluate the fairness of the coin. Aleatory uncertainty cannot be reduced with more information.

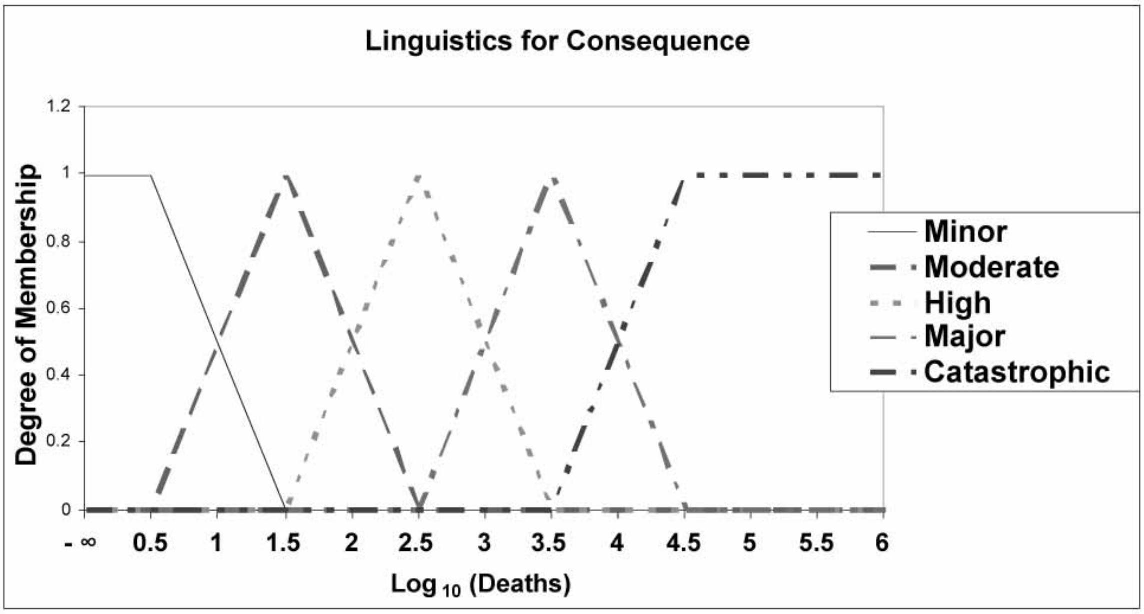
Figure 1. Belief/plausibility as bounds on probability



In addition to ambiguity, we have another type of uncertainty called vagueness. We have vagueness when we use linguistics (words) to classify events; for example, yesterday was *sunny*, public confidence in the stock market is *high*, etc. Vagueness is uncertainty as to how to classify a *known* event. For example, assume we know how tall John is, but instead of saying John is 6 feet 2 inches tall we categorize John as *tall* without a precise definition of *tall*. The linguistic (word) *tall* is vague. Vagueness can be addressed using the mathematics of fuzzy sets.

A simple example of fuzzy sets is as follows. Consider a random variable for consequence as “the number of deaths from a terrorist attack” for which we take the range as [0, 10^6]. For estimating the consequence from a particular scenario we may choose to reason at a higher level than a specific number of deaths for two reasons: (a) there is too much uncertainty to distinguish between say 1,000 and 2,000 deaths, and (b) when comparing scenarios with widely different consequences, such as blowing up a building to detonating a nuclear device, we have orders of magnitude difference in the consequence. Suppose we partition the range with crisp sets commensurate with the *accuracy* to which we wish to measure consequence; for example, [0, 10], [10, 100], [100, 1,000), [1,000, 10^4), [10^4, 10^6]. We have defined sets, subsets of the range, at the *fidelity* to

Figure 2. Fuzzy sets for consequence (deaths)



which we wish to reason. We can also assign names to these sets: *minor* for [0, 10), *moderate* for [10, 100), *high* for [100, 1,000), *major* for [1,000, 10^4), and *catastrophic* for [10^4, 10^6]. We have assigned a linguistic (name) to the crisp sets of interest. But there is a problem with our crisp sets. If 999 people die the consequence is *high* but if 1,000 people die the consequence is *major*; although the crisp sets solve the problem of reasoning at too fine a level, they suffer from the problem of sharp boundaries. We really want to consider 999 deaths as both high *and* major to some degree, and we can do so by making our sets fuzzy. Specifically we define minor as "up to *about* 10," *moderate* as "between *about* 10 and *about* 100," *high* for "between *about* 100 and *about* 1,000," *major* for "between *about* 1,000 and *about* 10^4," and *catastrophic* for "greater than *about* 10^4." Degrees of membership mathematically define these fuzzy sets as indicated in Figure 2.

Uncertainty involving both ambiguity and vagueness can be addressed by extending belief/plausibility to fuzzy sets.[6] Thus, we can apply the belief/plausibility measure of uncertainty to fuzzy sets as well as to crisp sets.

For example, given degrees of evidence assigned to crisp intervals in the range for deaths, such as 0.7 for [10, 1,000] and 0.3 for [1, 50,000], we can calculate the belief/plausibility for the fuzzy sets defined for deaths in Figure 2.[vi] For *minor* consequences belief/plausibility is 0/0.65. For *moderate* consequences, belief/plausibility is 0/1. For *high* consequences, belief/plausibility is 0/1. For *major* consequences, belief/plausibility is 0/0.65. For *catastrophic* consequences, belief/plausibility is 0/0.3.

Evaluation of Risk for an Act of Terrorism

Evaluation of risk for an intentional terrorist act is much harder than evaluation of risk for a *dumb* random event. The uncertainty associated with a terrorist act involves significant epistemic uncertainty. A terrorist attack is not a random event, it involves a specific scenario that is selected, planned, and implemented by the adversary.[vii] Consider the failure of a specific building in response to an earthquake, a random *dumb* event. The risk from the earthquake considers the likelihood of the earthquake, the fragility of the building (used to calculate the response of the building to the earthquake), and the number of people killed if the building fails. The magnitude of the earthquake is independent of the fragility of the building. However, for an intentional terrorist attack against the building, the adversary estimates the resources required to destroy the building based on an evaluation of the fragility of the building, and decides if the potential consequences are worth the effort to bring the resources to bear necessary to destroy the building. The adversary has a choice as to which building to attack, the earthquake does not.

The terrorists have a choice, so the number of scenarios is enormous (hundreds of millions). Even if we as a defender focus on a small subset of targets for evaluation, such as the U.S. Department of Defense nuclear weapons sites, the terrorists may choose targets outside our consideration, such as a water dam. A complete evaluation of f_{Ai}, the frequency of an attack using scenario "i", must address that choice.

Figure 3. Degrees of evidence (probabilities) for P_E and C

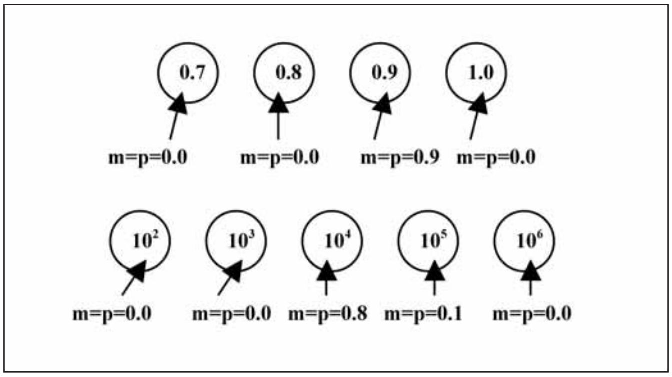


Figure 4. Degrees of evidence (nested) for f_A

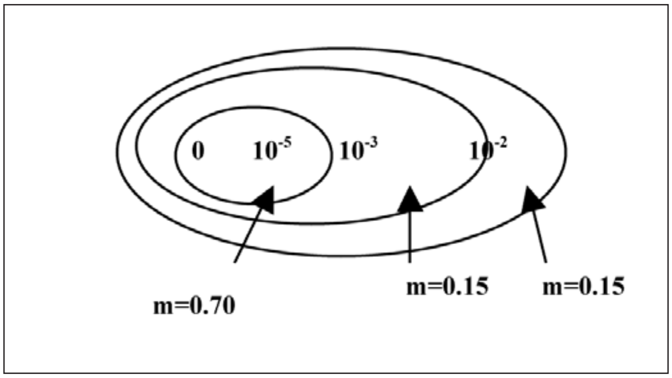
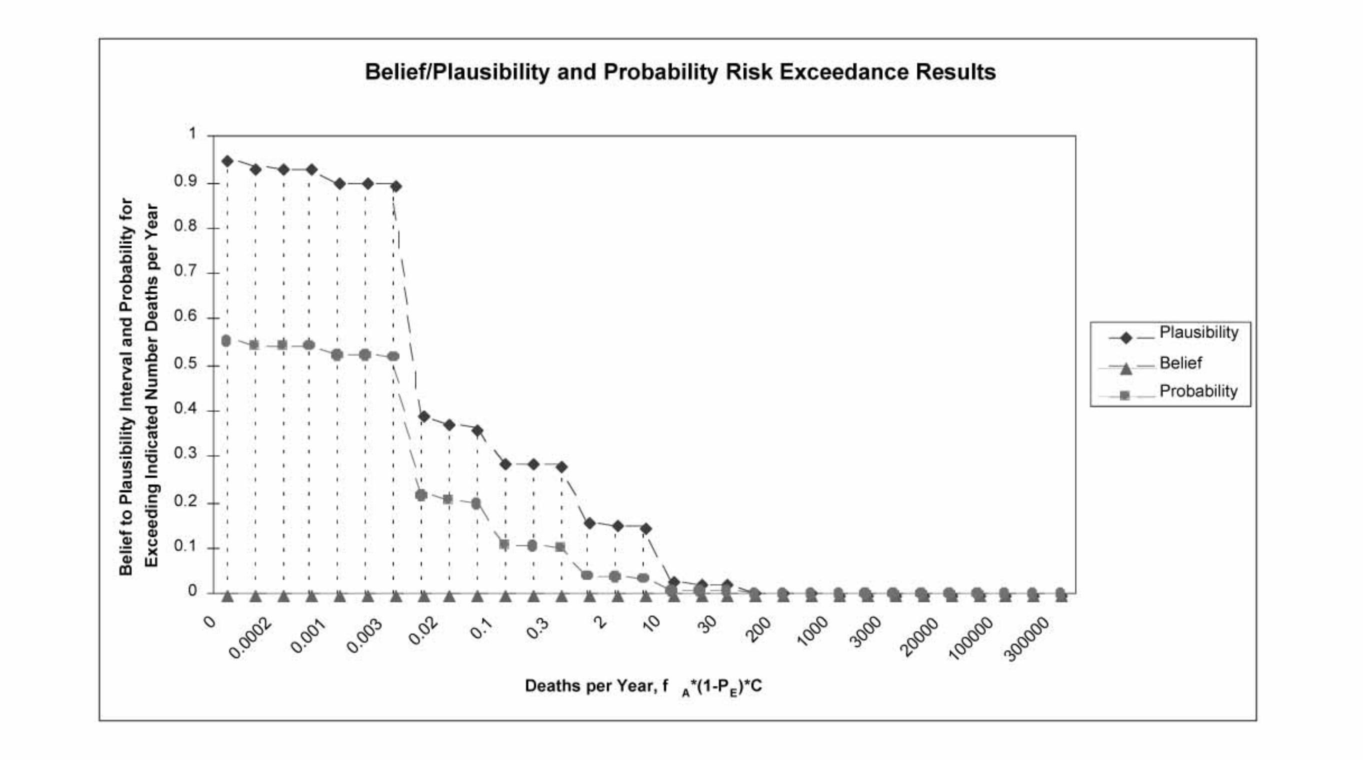


Figure 5. Risk exceedance results using belief/plausibility and probability



There is significant epistemic uncertainty for the defender as to the scenario(s) that the adversary will select. The adversary has epistemic uncertainty as to the effectiveness of protective measures employed by the defender, including intelligence gathering efforts to prevent scenarios from being implemented, security systems in place to defeat an attack, and the effectiveness of measures to mitigate consequences.

We have developed an adversary/defender model for evaluating risk from a terrorist act.[5,7,8] The defender part of the model evaluates risk numerically *for selected scenarios* using belief/plausibility distributions based on degrees of evidence assigned to each of the variables. The adversary part of the model is a fuzzy set, linguistic approximate reasoning tool developed by "thinking like the adversary" and it *provides information for selecting scenarios to evaluate in the defender model.*

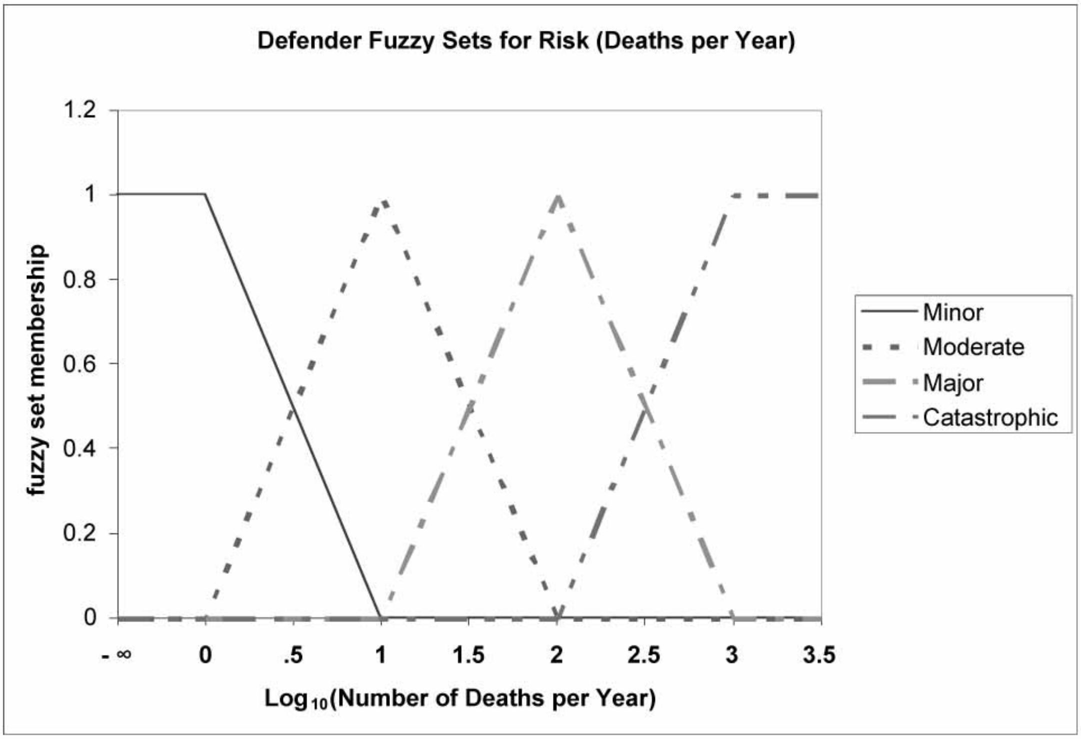
Defender Model

The defender model will be explained using a simple example for one scenario; the "i" subscript for the scenario will be suppressed.[viii] Let the sample spaces for f_A, P_E, and C be:

$f_A = [0, 10]$ with units of per year

$P_E = [0, 1]$ dimensionless

Figure 6. Fuzzy sets for risk (deaths per year)



C = [0, 10^7] with units of number of deaths.

It is assumed that these three random variables are noninteractive.[ix] Assume that the scenario is sufficiently well specified such that P_E and C can be modeled probabilistically with the degrees of evidence (probabilities) given in Figure 3.[x] (In Figure 3 "m" denotes a degree of evidence which reduces to a probability "p" if the focal elements are singletons. See Appendix A.)

Assume f_A is assigned the degrees of evidence given in Figure 4. The evidence is over intervals; specifically, 0.7 is evidence for the interval [0, 10^{-5}], 0.15 is evidence for the interval [0, 10^{-3}], and 0.15 is evidence for the interval [0, 10^{-2}].

Evaluating Equation 1 for this scenario, Figure 5 provides the complementary cumulative belief/plausibility (Bel/Pl) distribution for risk.[xi] These results were calculated with the BeliefConvolution code, a Java code written by the author. The result is shown as a likelihood of exceedance; for example the plausibility of more than 0.1 deaths per year is about 0.3. The expected value interval for risk is [0, 6.4] deaths per year.

For any event A, Bel(A) + Pl(A^C) = 1 where A^C is the complement of event A. For example, the belief/plausibility of greater than 100 deaths per year is 0/0.00374; the belief/plausibility of less than or equal to 100 deaths per year is 0.99625/1.0.

As indicated in Figure 4, the information for f_A is not specific enough to justify the use of a probability distribution. If we *force* f_A to be modeled probabilistically we will lose much of the uncertainty inherent in the evidence. To illustrate this, a probability distribution can be generated for f_A assuming a uniform probability distribution.

For example, approximate the sample space as the discrete set f_A = {0, 10^{-5}, 10^{-4}, 10^{-3}, 10^{-2}, 10^{-1}, 1, 10}. For the focal element {0, 10^{-5}} the degree of evidence is 0.7 and the probabilities are 0.7/2 for both 0 and 10^{-5}. For the focal element {0, 10^{-5}, 10^{-4}, 10^{-3}} the degree of evidence is 0.15 and the probabilities are 0.15/4 for 0, 10^{-5}, 10^{-4}, and 10^{-3}. For the focal element {0, 10^{-5}, 10^{-4}, 10^{-3}, 10^{-2}} the degree of evidence is 0.15 and the probabilities are 0.15/5 for 0, 10^{-5}, 10^{-4}, 10^{-3}, and 10^{-2}. Summing, the probability distribution for {0, 10^{-5}, 10^{-4}, 10^{-3}, 10^{-2}} is {0.4175, 0.4175, 0.0675, 0.0675, 0.03}.

Figure 5 also shows the complementary cumulative probability distribution for risk using this *assumed* probability distribution for f_A. The expected value (mean) of the probability distribution is 1.5 deaths per year. The loss of uncertainty is evident in Figure 5 when the results from the probability model are compared to the results from the belief/plausibility model.

Figure 7. Risk in terms of fuzzy sets

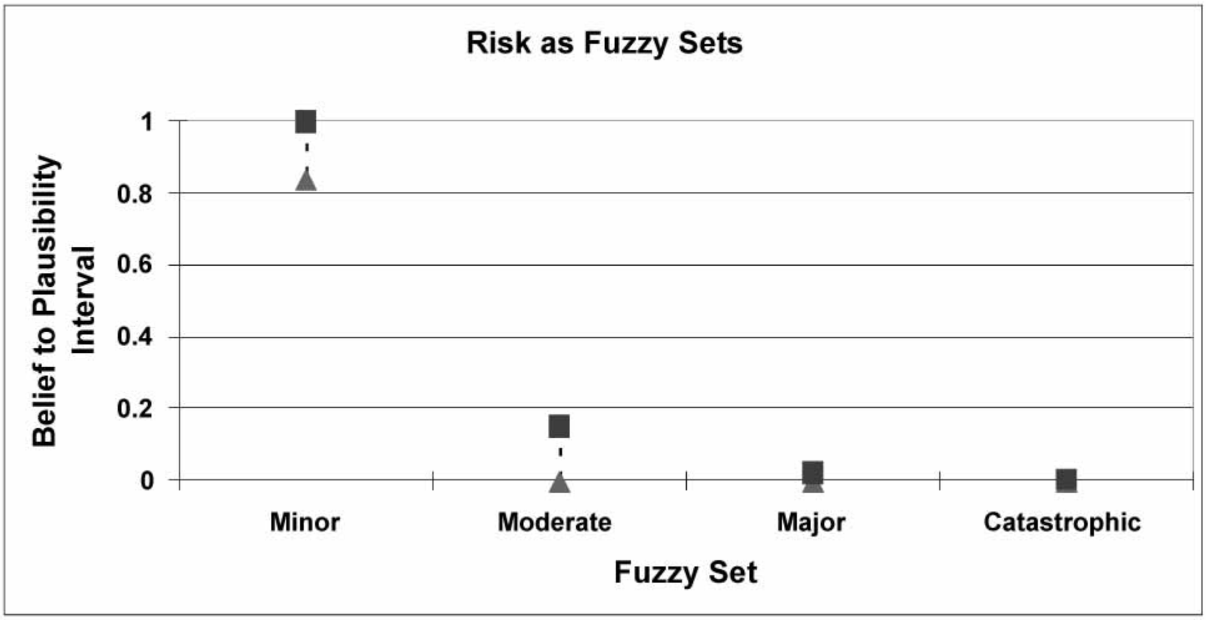


Figure 8. Risk as exceedance frequency of consequence

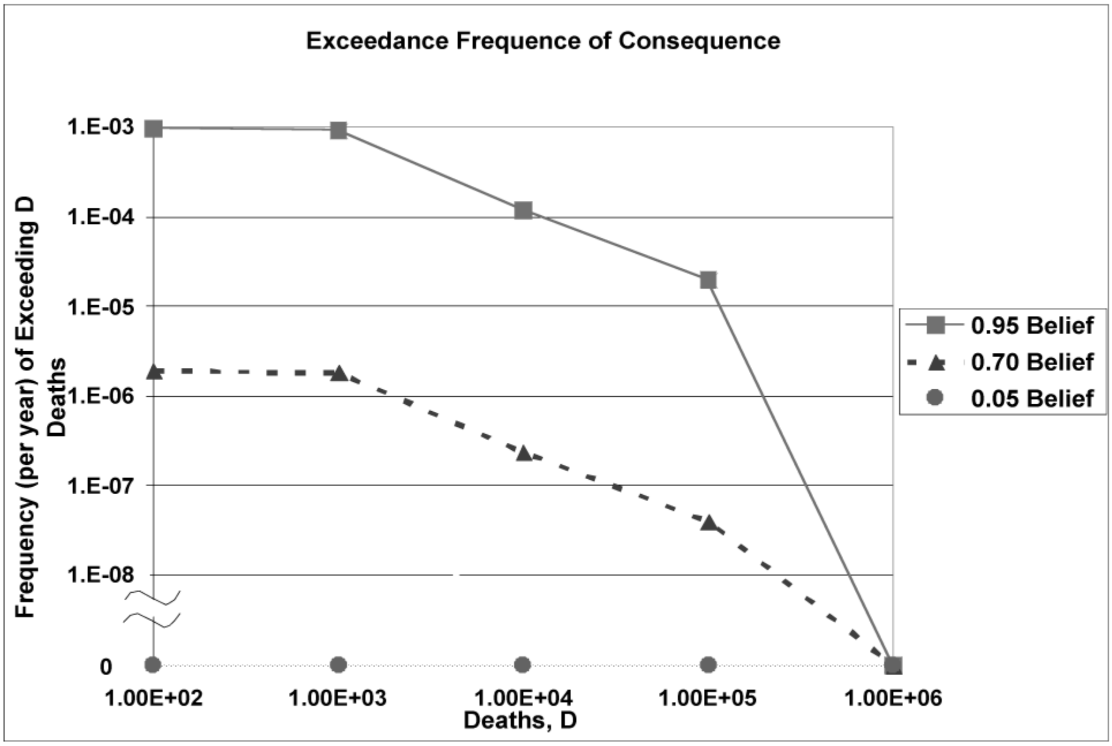
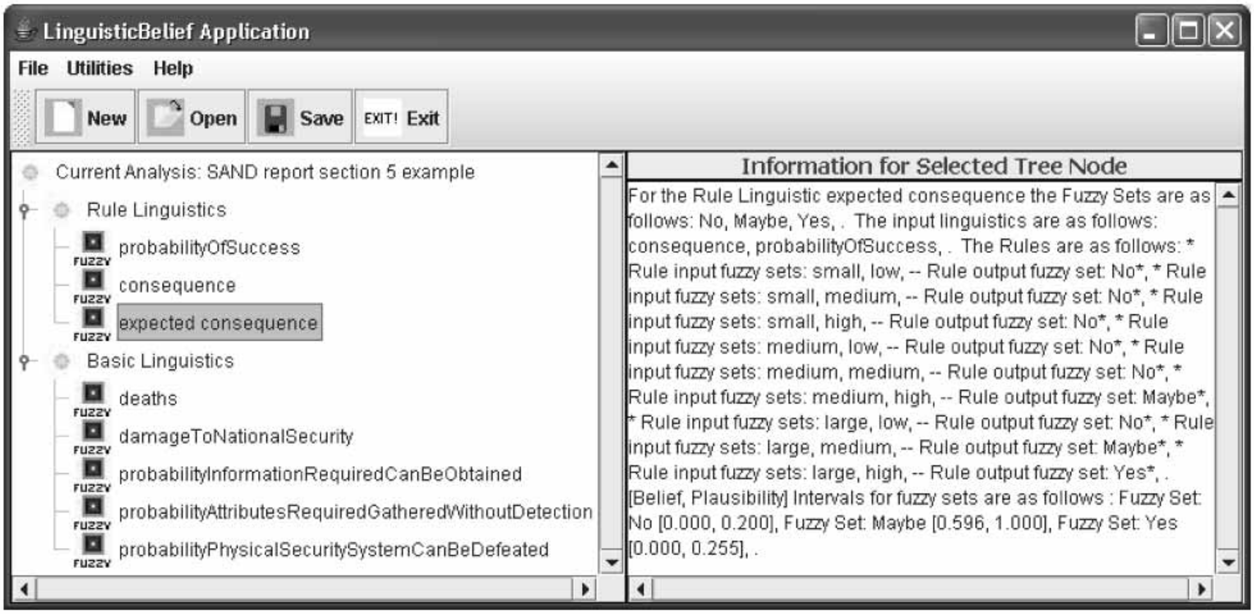


Figure 9. Adversary model in LinguisticBelief code



For the Rule Linguistic expected consequence the Fuzzy Sets are as follows: No, Maybe, Yes, . The input linguistics are as follows: consequence, probabilityOfSuccess, . The Rules are as follows: * Rule input fuzzy sets: small, low, -- Rule output fuzzy set: No*, * Rule input fuzzy sets: small, medium, -- Rule output fuzzy set: No*, * Rule input fuzzy sets: small, high, -- Rule output fuzzy set: No*, * Rule input fuzzy sets: medium, low, -- Rule output fuzzy set: No*, * Rule input fuzzy sets: medium, medium, -- Rule output fuzzy set: No*, * Rule input fuzzy sets: medium, high, -- Rule output fuzzy set: Maybe*, * Rule input fuzzy sets: large, low, -- Rule output fuzzy set: No*, * Rule input fuzzy sets: large, medium, -- Rule output fuzzy set: Maybe*, * Rule input fuzzy sets: large, high, -- Rule output fuzzy set: Yes*, . [Belief, Plausibility] Intervals for fuzzy sets are as follows : Fuzzy Set: No [0.000, 0.200], Fuzzy Set: Maybe [0.596, 1.000], Fuzzy Set: Yes [0.000, 0.255], .

We can summarize risk for this scenario using fuzzy sets. We implemented Yager's technique in our BeliefConvolution code to calculate belief/plausibility for fuzzy sets.[6] For example, assume the fuzzy sets of Figure 6 are used.

We can also express risk as an "exceedance frequency of consequence" using a belief/plausibility measure. Using belief/plausibility, $L_i(c)$ in Equation 6 is an interval: [belief, plausibility]. A conservative estimate for the exceedance frequency of consequence can be calculated using plausibility for the excedance likelihood of consequence, $L_i(c)$, and belief for the nonexceedance likelihood for the result, Freq(c).[5] For the example scenario, C has a probability distribution, so belief and plausibility for C are both probability, and $L_i(c)$ is a single value, the probability. Figure 8 summarizes the results for the example scenario.[xii]

With 0.95 belief the frequency of exceeding 1×10^5 deaths is not greater than 2×10^{-5} per year; with 0.70 belief the frequency of exceeding 1×10^5 deaths is not greater than 4×10^{-8} per year.

Defender Efforts to Reduce Risk

So far consequence has been considered to be of one type, e.g., deaths. Many additional types of consequences may be of concern, such as: economic loss (dollars), damage to national security, fear in the populace, etc. If the consequences are numeric, such as deaths and economic loss, a common measure of consequence can be used, such as "willingness to pay," and the different types of consequences can be summed using this common measure.[xiii] Willingness to pay is the dollar amount (present worth) you are willing to pay to prevent a consequence of a certain type and magnitude. For scenario "i", C_{ij} represents consequence of type "j" expressed in a common measure. Total consequence is the sum over all the consequence types.

$$C_i = \sum_j C_{i_j} \tag{7}$$

To reduce the risk for a terrorist act, the defender can: (a) detect and stop the scenario during the formulation stage, (b) defeat the attack, and/or (c) mitigate (lower) the consequence. In practice, a combination of these approaches is used.

The effectiveness of measures to defeat the attack is explicitly considered in the P_{Ei} term.

To explicitly include the effectiveness of mitigation, we replace C_{ij} with $C_{ij\ mitigated}$ where $C_{ij\ mitigated}$ credits measures in place to reduce the consequence type "j" given adversary success.[xiv]

To explicitly consider the effectiveness of defender efforts to stop a scenario during the formulation stage, the likelihood of attack will be segregated into two factors: the likelihood that the adversary selects the scenario and the likelihood that the scenario is not detected during its formulation stage. Specifically, f_{Ai}, will be expressed as:

$$f_{A_i} = f_{ASelect_i} * (1 - P_{Detect\ resources_i}) \tag{8}$$

where $f_{ASelect\ i}$ is the frequency at which the scenario is selected for implementation by the adversary, and $P_{Detect\ resources\ i}$ is the probability that the scenario, once selected, is detected during the formulation stage.[xv]

The effectiveness of intelligence gathering efforts is considered in $P_{\text{Detect resources } i}$ and the effectiveness of the security system is considered in P_{Ei}.

These additional factors can be incorporated into an evaluation of risk. For example, Equation 1can be expressed as:

$$Risk_i = f_{ASelect_i} * (1 - P_{Detectresources_i}) * (1 - P_{E_i}) * \sum_j C_{i\ j\ Mitigated} \qquad (9)$$

and Equation 3 can be expressed as:

$$F_{A_i} = f_{ASelect_i} * (1 - P_{Detectresources_i}) * (1 - P_{E_i}) \qquad (10)$$

All the variables for risk for a specific scenario depend only on that scenario except for $f_{A\ Select\ i}$. $f_{A\ Select\ i}$ depends on the adversary perception of the attractiveness of the scenario in the context of *all* other scenarios, including those for targets other than the target for the scenario of concern. The fact that the adversary has a choice of scenarios affects the adversary decision for selecting the particular scenario of concern.

Adversary Model

To evaluate risk using the defender model, scenarios of concern must be identified. The process of selecting scenarios requires that the defender reason from the perspective of the adversary, and this process involves a complicated consideration of many factors each with significant uncertainty.

Since the adversary has a choice of scenarios, unless all the factors of importance to the adversary are *good* the adversary will discard a scenario and consider other scenarios. Instead of a precise numerical assessment, the adversary uses more of a yes/no decision process for such factors as:

- Are the consequences of the type desired?
- Are the potential consequences highly likely to be of sufficient magnitude?
- Given the perceived magnitude of the consequences and the perceived level of protection, is it worth gathering the resources needed to have a high assurance of success?
- What are other scenarios that require fewer resources and have acceptable consequences?

That is, the adversary selects scenarios that are highly likely to succeed and maximize consequences while making effective use of resources within the constraint of the pool of resources available. The adversary spends more effort in designing, planning, and rehearsing the scenario for a high likelihood of success rather than estimating a precise numerical value for the likelihood of success.[xvi]

The adversary model evaluates scenarios using an approximate reasoning rule base for how the adversary selects a scenario. Each variable in the rule base is segregated into fuzzy sets. The fuzzy sets represent purely linguistic terms; there is no numeric definition of the fuzzy sets as in Figure 2.[xvii] To capture the significant uncertainty inherent in the *defender thinking like the adversary*, the model allows evidence to be assigned to combinations of fuzzy sets for each variable, and uncertainty is propagated up the rule base using the belief/plausibility measure of uncertainty.[xviii] A Java code, LinguisticBelief, was written by the author to automate the evaluation. The adversary model is best explained by a simple example.

Table 1. Focal elements for one scenario

Variable	Focal Element	Evidence
Deaths	{Major, Catastrophic} {Moderate, Major}	0.8 0.2
Damage to National Security	{Insignificant, Significant} {Significant, Very Significant}	0.1 0.9
Probability Attributes Required Gathered Without Detection	{Medium} {Medium, High}	0.7 0.3
Probability Information Required Can be Obtained	{Medium} {Medium, High}	0.15 0.85
Probability Physical Security System Can be Defeated	{Medium, High}	1.0

From the perspective of the adversary, the *expected consequence* for a particular scenario is defined as the consequence as perceived by the adversary—weighted by the likelihood that the scenario can be successfully accomplished—as perceived by the adversary. It is assumed that the goal of the adversary is to maximize expected consequence. Assume the following approximate reasoning process on the part of the adversary, where x indicates convolution per the rule base:[xix]

- Expected Consequence = Probability of (Adversary) Success x Consequence
- Probability of Success = Probability Attributes Required Gathered Without Detection x Probability Information Required Can be Obtained x Probability Physical Security System Can be Defeated
- Consequence = Deaths x Damage to National Security

Figure 9 shows this example as modeled in the LinguisticBelief code.

Assume the following linguistics (fuzzy sets) for each variable:

- Expected Consequence = {No, Maybe, Yes}
- Probability of Success = {Low, Medium, High}
- Consequence = {Small, Medium, Large}
- Probability Attributes Required Gathered Without Detection = {Low, Medium, High}
- Probability Information Required Can be Obtained = {Low, Medium, High}
- Probability Physical Security System Can be Defeated = {Low, Medium, High}

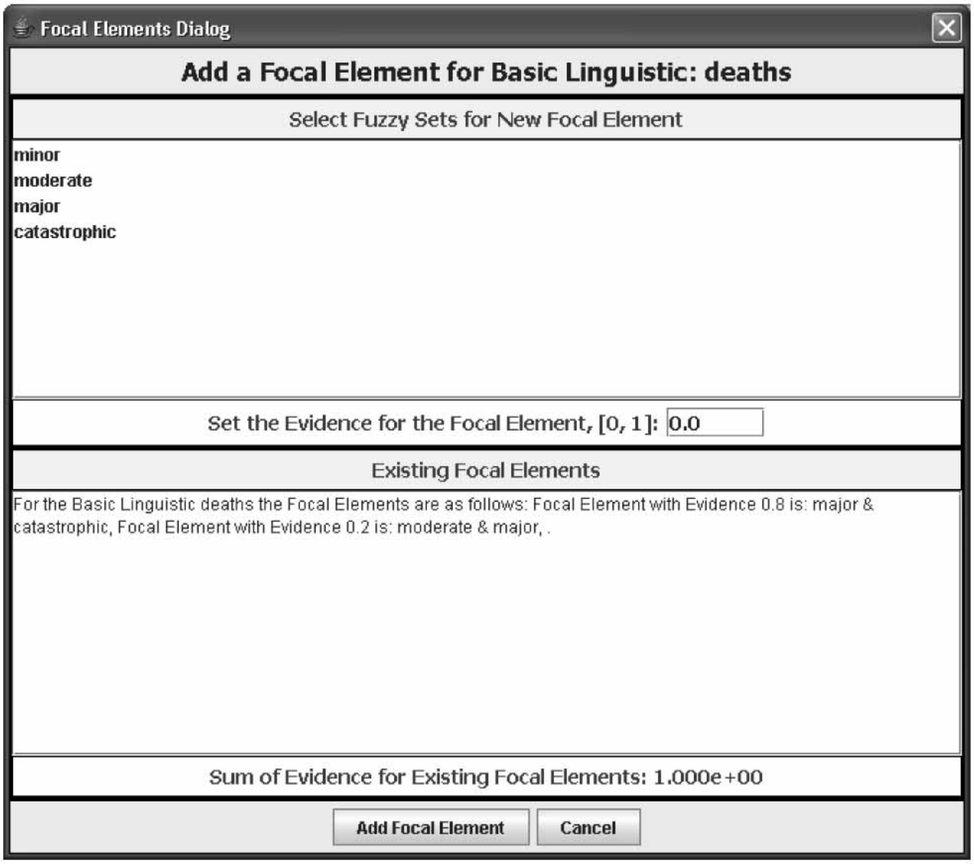
Figure 10. Rules for expected consequence

Rules for RuleLinguistic: expected consequence

Fuzzy Set for Input Linguistic: consequence	Fuzzy Set for Input Linguistic: probabilityOfSuccess	Output Fuzzy Set for Rule (blank if rule not set)
small	low	No
small	medium	No
small	high	No
medium	low	No
medium	medium	No
medium	high	Maybe
large	low	No
large	medium	Maybe
large	high	Yes

Specify Output Fuzzy Set for Selected Rule: No

Figure 11. Focal elements for deaths



Add a Focal Element for Basic Linguistic: deaths

Select Fuzzy Sets for New Focal Element

minor
moderate
major
catastrophic

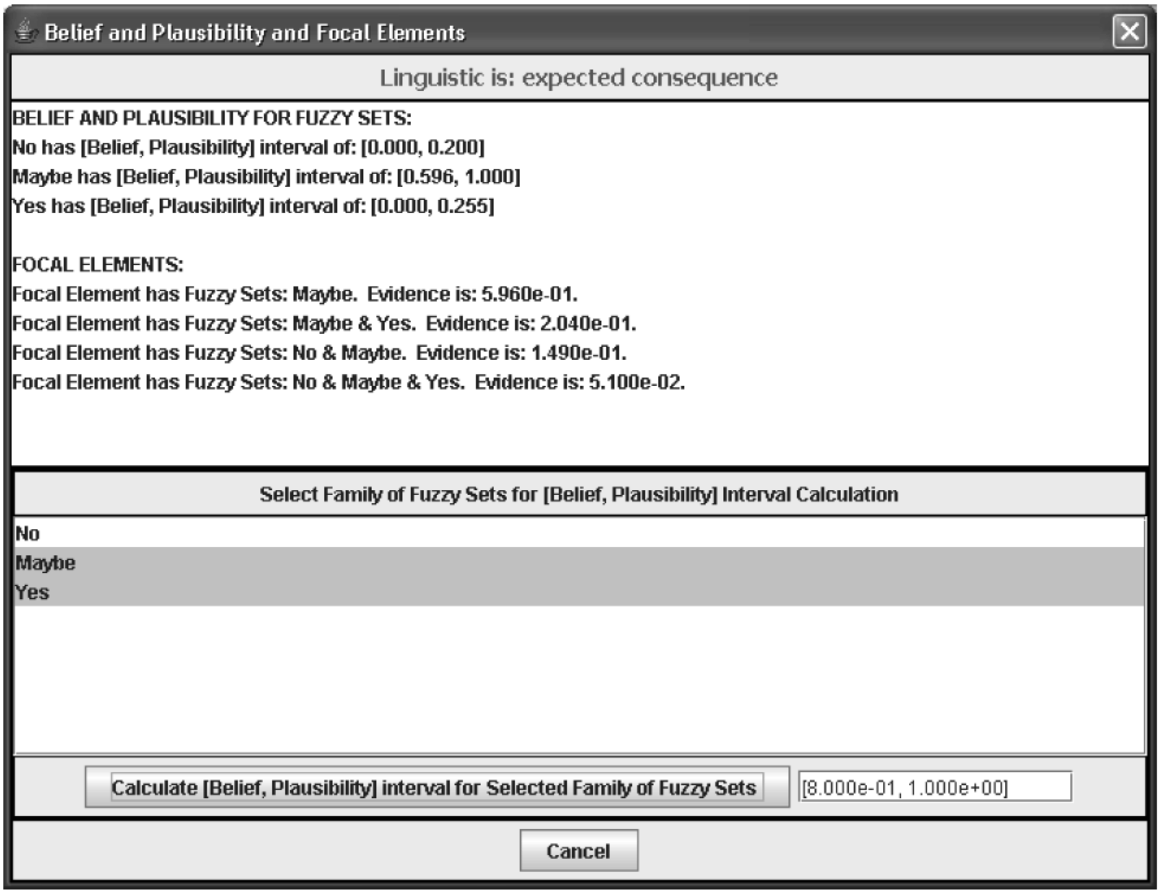
Set the Evidence for the Focal Element, [0, 1]: 0.0

Existing Focal Elements

For the Basic Linguistic deaths the Focal Elements are as follows: Focal Element with Evidence 0.8 is: major & catastrophic, Focal Element with Evidence 0.2 is: moderate & major, .

Sum of Evidence for Existing Focal Elements: 1.000e+00

Figure 12. Results for expected consequence



Linguistic is: expected consequence

```
BELIEF AND PLAUSIBILITY FOR FUZZY SETS:
No has [Belief, Plausibility] interval of: [0.000, 0.200]
Maybe has [Belief, Plausibility] interval of: [0.596, 1.000]
Yes has [Belief, Plausibility] interval of: [0.000, 0.255]

FOCAL ELEMENTS:
Focal Element has Fuzzy Sets: Maybe.  Evidence is: 5.960e-01.
Focal Element has Fuzzy Sets: Maybe & Yes.  Evidence is: 2.040e-01.
Focal Element has Fuzzy Sets: No & Maybe.  Evidence is: 1.490e-01.
Focal Element has Fuzzy Sets: No & Maybe & Yes.  Evidence is: 5.100e-02.
```

Select Family of Fuzzy Sets for [Belief, Plausibility] Interval Calculation

No
Maybe
Yes

[8.000e-01, 1.000e+00]

- Deaths = {Minor, Moderate, Major, Catastrophic}
- Damage to National Security = {Insignificant, Significant, Very Significant}

The fuzzy sets for expected consequence indicate attractiveness of the scenario to the adversary; for example, *no* indicates that the scenario is not attractive to the adversary.

A portion of the approximate reasoning rule base—the rules for expected consequence—is shown in Figure 10 from the LinguisticBelief code:

The complete rule base reflects the following. As shown in Figure 10, Expected Consequence *yes* indicates an attractive scenario for the adversary and requires that Probability of Success (for the adversary) be *high* and consequence be *large*. Other rules (not shown here) for probability of success *high* require a *high* value for each of the three constituent probabilities. Rules for consequence *large* (not shown here) require that the combination of deaths and/or damage to national security be severe enough from the viewpoint of the adversary.

The rule base is evaluated for each scenario of concern. For example, assume the following focal elements for the variables for a particular scenario given in Table 1.

Figure 11 shows the focal elements for deaths in the LinguisticBelief code.

Using the LinguisticBelief code, the following results were obtained for [belief, plausibility]:

- Probability of Success: [0, 0] for Low, [0.74, 1.0] for Medium, [0, 0.26] for High
- Consequence: [0, 0] for Small, [0, 0.20] for Medium, [0.80, 1.0] for Large
- Expected Consequence: [0, 0.20] for No, [0.60, 1.0] for Maybe, [0, 0.26] for Yes

The results for this scenario indicate that although the adversary (defender thinking like the adversary) estimates a *large* consequence to be likely (belief/plausibility of 0.80/1.0), the adversary expects probability of success to only be *medium* (belief/plausibility of 0.74/1.0), resulting in an overall estimate that expected consequence will be *maybe* (belief/plausibility of 0.60/1.0).

Figure 13. Complementary cumulative belief/plausibility distribution for expected consequence for one scenario

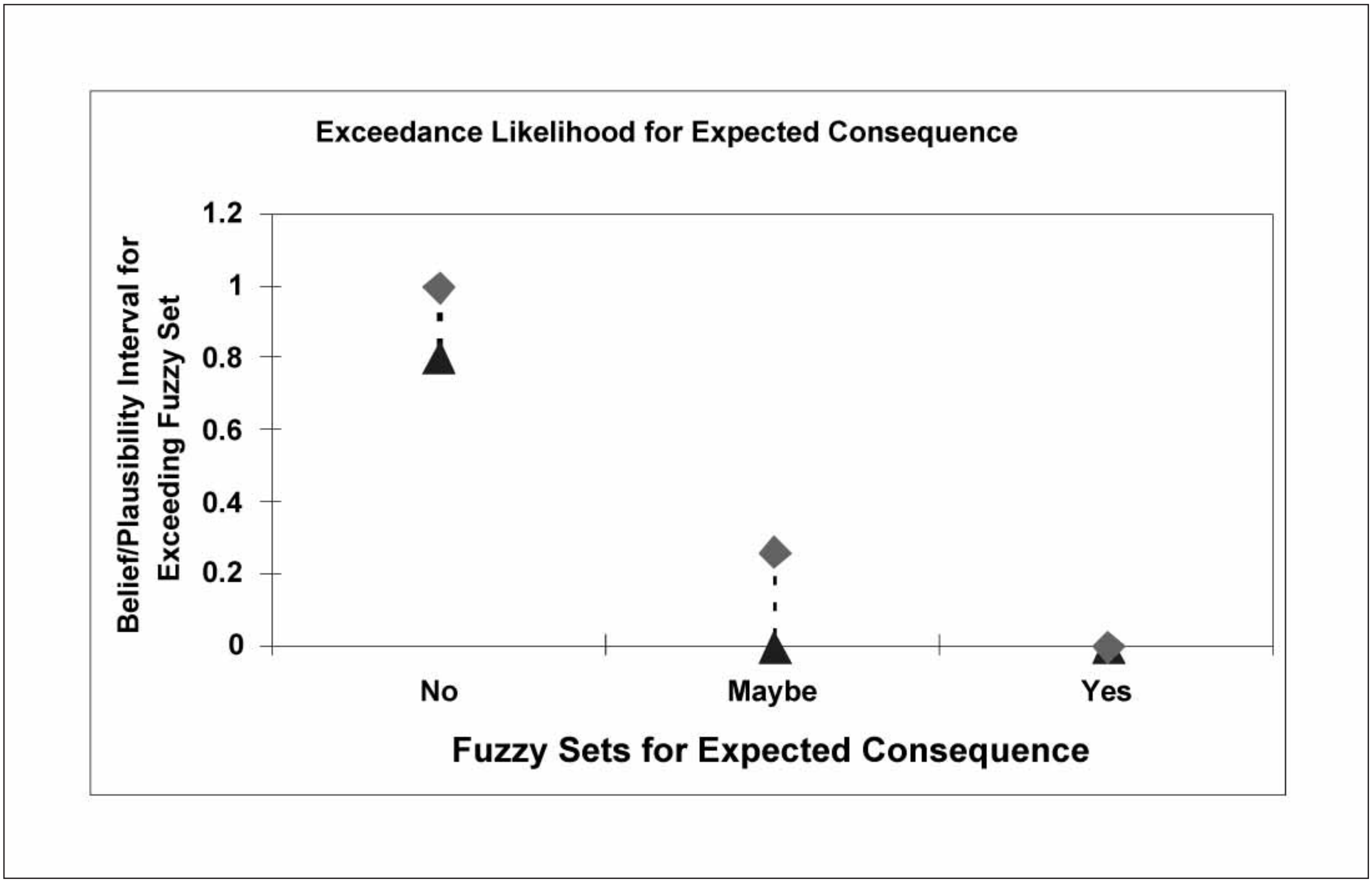


Figure 12 shows the result from LinguisticBelief for expected consequence. Figure 13 shows expected consequence as a complementary cumulative belief/plausibility distribution.

As the defender thinking like the adversary, we rank scenarios by plausibility.[xx] For the example scenario the plausibility of expected consequence being *yes* is 0.26 (the plausibility of expected consequence exceeding *maybe* from Figure 13). Since the adversary has a choice of scenarios, we should examine other scenarios until ones with a high plausibility of *yes* for expected consequence are identified.

Summary

Evaluation of risk from acts of terrorism involves considerable epistemic uncertainty which can be captured and propagated using the belief/plausibility measure of uncertainty from the Dempster-Shafer Theory of Evidence. The risk from an act of terrorism depends on the scenario employed by the adversary and on the likelihood that the adversary selects that scenario. For a given scenario, the risk can be evaluated numerically with a defender model.

The scenarios to be evaluated in the defender model can be selected using an adversary model which uses approximate reasoning on fuzzy sets for linguistic variables. Uncertainty in the evaluation due to the defender “thinking like the adversary” is captured using the belief/plausibility measure.

Software has been written to automate the evaluation of both the defender and adversary models. The Java code BeliefConvolution is used for the numerical evaluation of risk for the defender model; the Java code LinguisticBelief is used for the linguistic evaluation of risk for the adversary model.

Acknowledgments

The use of a linguistic rule base for modeling the adversary is based on concepts from the Logic Evolved Decision (LED) methodology developed at Los Alamos National Laboratory (LANL) by Terry Bott and Steve Eisenhawer, extended in this work to include belief/plausibility as the measure of uncertainty. The numerical model for the defender benefited from the work and suggestions of Jon Helton at Arizona State University.[9,10]

The evaluation of belief/plausibility for fuzzy sets uses the technique developed by Ronald Yager at Iona College.[6]

Scott Ferson of Applied Biomathematics provided suggestions and helpful reference material during the formulation of the

concepts used in this work. The RAMAS RiskCalc software (version 4.0) developed by Ferson, et al., was used to check test case results of the BeliefConvolution code.

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Appendix A. Summary of the Belief/Plausibility Measure of Uncertainty

The references provide detailed information on belief/plausibility. This appendix summarizes the belief/plausibility measure of uncertainty for crisp sets. Belief/plausibility can also be applied to fuzzy sets as discussed in the references.[5,6]

The axioms for belief/plausibility require that the focal elements for a universe of discourse be countable. This appendix addresses belief/plausibility for discrete sets. Belief/plausibility can also be applied to intervals of real numbers, as discussed in the references.

A random variable is a real-valued function defined on a sample space. The values for a random variable can be represented as a set of all possible numerical values; for example, X = {x | x an element of [0,1]}.[xxi] The uncertainty for a random variable can be expressed by assigning a *likelihood* to events in its set. Therefore, a complete description of the random variable consists of two parts: (1) the set of all possible values and (2) an uncertainty measure on that set. A random vector is a combination of random variables and the random vector has a set of values (tuples). Convolution is the process of combining uncertainty distributions of random variables to produce an uncertainty distribution for a function defined on the random vector.

Consider two discrete random variables with ranges defined as follows: [xxii]

$$\begin{aligned} X &= \{x_i \mid i = 1,2,\ldots,n\} \\ Y &= \{y_j \mid j = 1,2,\ldots,m\} \\ X\,x\,Y &= \{<x,y> \mid x \in X, y \in Y\} \end{aligned} \qquad \text{(A-1)}$$

where x and y are real numbers. The random vector is the Cartesian product X x Y. A subset of the Cartesian product X x Y is called a relation.

We are interested in a function defined on a random vector that maps to the set of real numbers, f:X x Y→Reals. For example we may wish to perform addition, X + Y, or multiplication X * Y.[xxiii] Let f(x,y) = z. The mapping f produces the solution:

$$Z = \{z \mid f(x,y) = z, x \in X, y \in Y\} \qquad \text{(A-2)}$$

Note that more than one <x, y> can have the same z. For example, if f is X + Y then <2, 3> and <1, 4> both have z = x + y = 5.

Equation A-2 provides the values for the function of interest. To consider uncertainty, we also need to generate a likelihood for each of these values by convoluting the likelihood distributions that represent uncertainty for X and Y. As subsequently discussed, there are measures of uncertainty besides probability. The mathematics for convolution depend on the measure selected for uncertainty.

Denote the power set of X as Pow(X). Pow(X) is defined as the set of all subsets X including the null set. For example, the power set of X = {a, b, c} is Pow(X) = {null, {a}, {b}, {c}, {a, b}, {a, c}, {b, c}, {a, b, c}}. For a finite set with n elements the power set has 2^n elements. A general measure of uncertainty, U, is a mapping on the power set: U:Pow(X)→[0, 1]. Using the mathematics for the uncertainty measure, a likelihood can be calculated for each event in X.

Let A be a subset of X. A is also called an event for the random variable. The elements of X are unique values (mutually exclusive). In general, events are not mutually exclusive since subsets of X can have common elements.[xxiv]

Since the sample space has unique elements, and the random variable is a mapping of the sample space to the reals, the value of a random variable will be unique, but there is uncertainty as to this value. This type of uncertainty is called ambiguity. A measure of ambiguity is called a fuzzy measure in the literature.

A general fuzzy measure of interest for our evaluation of risk is belief, which can be explained by considering "degrees of evidence" assigned to the elements of Pow(X). Let m denote a degree of evidence. "m" is a function defined as follows:

$$\begin{aligned} &m : Pow(X) \rightarrow [0,1] \\ &m(null) = 0 \\ &\sum_{A \in Pow(X)} m(A) = 1 \end{aligned} \qquad \text{(A-3)}$$

The elements of Pow(X) with non-zero degrees of evidence are called the focal elements of X. The focal elements of X are the subsets (events) of X on which the evidence focuses. The focal elements form the body of evidence. The ambiguity type of uncertainty is completely specified by the body of evidence.

In terms of degrees of evidence, belief (Bel) and its dual fuzzy measure plausibility (Pl) are defined as follows for any A and B in Pow(X):

$$\begin{aligned} Bel(A) &= \sum_{B \mid B \subseteq A} m(B) \\ Pl(A) &= \sum_{B \mid A \cap B \neq 0} m(B) \end{aligned} \qquad \text{(A-4)}$$

m(A) represents the evidence that the value of the random variable is *exactly* in A (in A only). Bel(A) represents the evidence that the value of the random variable is in A or any subset of A. Pl(A) represents the evidence that the value of the random variable is in A, in any subset of A, or any set that overlaps (is not disjoint) with A.

Bel(A) is a measure of the amount of information that implies A^C is false, where A^C is the complement of A. Pl(A) is a measure of the amount of information that implies A is true (i.e., does not negate "A is true").

One useful interpretation is that Bel(A) is a measure of the degree to which A *will* happen, and Pl(A) is a measure of the degree to which A *could* happen.

Two types of ambiguity are of interest: strife and nonspecificity. Strife (or discord) is present if there is more than one focal element. Nonspecificity is present if a focal element is not a singleton.

With a belief/plausibility distribution, a random variable X has an expected value interval [$E_*(X)$, $E^*(X)$] given by:

$$\begin{aligned} E_*(X) &= \sum_{all\ A_i \subseteq X} \inf(A_i) * m(A_i) \\ E^*(X) &= \sum_{all\ A_i \subseteq X} \sup(A_i) * m(A_i) \end{aligned} \qquad \text{(A-5)}$$

where A_i is an element of Pow(X) and m is a degree of evidence.[xxv]

Probability is a special case of belief. If the focal elements are singletons, then both belief and plausibility reduce to a common fuzzy measure, probability. For a discrete sample space, a probability measure assigns a degree of evidence to the elements of X (the singletons of Pow(X)), and the degree of evidence for an element, m, is called the probability, p, of the element. The degrees of evidence (probabilities) sum to 1.0.[xxvi]

The expected value, called the mean, of X is:

$$\overline{X} = \sum_{all\ x} x * p(x) \qquad \text{(A-6)}$$

Equation A-6 is a special case of Equation A-5 where $E_*(X) = E^*(X)$; that is, the expected value interval is a point value.

Belief/plausibility become necessity/possibility, respectively, if the focal elements are nested. The nested requirement means that for any two focal elements A and B, either A is a subset of B or B is a subset of A. Necessity/possibility is applicable to situations where the body of evidence is coherent; that is, where nonspecificity dominates over strife. This is in contrast to a situation where a probability measure is applicable: the evidence is precise but contradictory. It is important to note that necessity/possibility never reduce to probability due to the nesting requirement for focal elements, but belief/plausibility both reduce to probability for specific evidence.

A possibility distribution can be defined based on the degrees of evidence, and the possibility and necessity for any element of the power set can be calculated from the possibility distribution. The possibility distribution π is a mapping on the sample space X: $\pi : X \rightarrow [0,1]$.[xxvii] Let x denote an element of X. Let Π denote the possibility of any event A, a subset of X, and let N denote the necessity:

$$\begin{aligned} \Pi(A) &= \max_{x \in A} \pi(x) \\ N(A) &= \min_{x \notin A} (1 - \pi(x)) = 1 - \Pi(A^c) \end{aligned} \qquad \text{(A-7)}$$

where A^c denotes the complement of A.

The values for a function f:X x Y→Reals defined on the random vector X x Y are given in Equation A-2.

For the random vector X x Y each degree of evidence can be considered a binary relation R.[xxviii] That is, R is a subset of X x Y with non-zero m.

Let C denote any subset of X x Y. Using Equation A-4:

$$\begin{aligned} Bel(C) &= \sum_{R \subseteq X\,x\,Y | R \subseteq C} m(R) \\ Pl(C) &= \sum_{R \subseteq X\,x\,Y | R \cap C \neq null} m(R) \end{aligned} \qquad \text{(A-8)}$$

Following Equation A-5, the expected value interval for f is:

$$\begin{aligned} E_*(f : X\,x\,Y) &= \sum_{all\ R \subseteq X\,x\,Y} \inf[f(R)] * m(R) \\ E^*(f : X\,x\,Y) &= \sum_{all\ R \subseteq X\,x\,Y} \sup[f(R)] * m(R) \end{aligned} \qquad \text{(A-9)}$$

For each R, let R_X denote the projection of R on X and let R_Y denote the projection of R on Y (defined as follows):

$$\begin{aligned} R_X &= \{x \in X \mid <x, y> \in R \ for\ some\ y \in Y\} \\ R_Y &= \{y \in Y \mid <x, y> \in R \ for\ some\ x \in X\} \end{aligned} \qquad \text{(A-10)}$$

Define the marginal degrees of evidence m_x, the projection of m on X, and m_y, the projection of m on Y as:

$$\begin{aligned} m_X(A) &= \sum_{R | A = R_X} m(R) \ for\ all\ A \in Pow(X) \\ m_Y(B) &= \sum_{R | B = R_Y} m(R) \ for\ all\ B \in Pow(Y) \end{aligned} \qquad \text{(A-11)}$$

where $R|A=R_X$ means all relations R such that the projection of R onto X (R_X) is equal to A.

For any focal elements A and B in X and Y, respectively, the marginal bodies of evidence are said to be noninteractive if and only if:

$m(A \text{ x } B) = m_x(A) * m_Y(B)$, and

$m(R) = 0$ for all $R \neq A \text{ x } B$.[xxix]

This is the *product* definition of noninteraction, and is the type of noninteraction used in the evaluations discussed in this paper.[xxx]

Probabilistic independence is a special case of the product definition of noninteraction. For a probability measure, a degree of evidence is a probability for an element of the sample space, so any focal elements A and B are singletons of X and Y (call them a and b) and A x B has one element {<a, b>} with a probability P(a)*P(b).

Independence and noninteraction are discussed at length in a report by Ferson, et al.[12]

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References

1 Shafer, G. 1976. *A Mathematical Theory of Evidence*, Princeton University Press.

2. Klir. G. J., and B. Yuan 1995. *Fuzzy Sets and Fuzzy Logic, Theory and Applications*, Prentice Hall PTR.

3. Kaplan, S., and B. J. Garrick. 1981. On the Quantitative Definition of Risk, *Risk Analysis*, Vol. 1 No. 1, 11-27.

4. Dubois, D., and H. Prade. 1988. *Possibility Theory, An Approach to Computerized Processing of Uncertainty*, P

5. Darby, J. 2006. *Evaluation of Risk from Acts of Terrorism: The Adversary/Defender Model Using Belief and Fuzzy Sets*, SAND2006-5777, Sandia National Laboratories.

6. Yager, R. 1986. Arithmetic and other operations on Dempster Shafer Structures, *International Journal of Man-Machine Studies*, 25: 357-366.

7. Merkle, P. 2006. *Extended Detection and Defense: 1. Adversary-Defender Modeling Grammar for Vulnerability Analysis and Threat Assessment*, SAND2006-1484.

8. Snell, M., 2006. Estimation of Probability of Adversary Mission Success, *Proceedings of the 47th Annual Meeting of Institute of Nuclear Materials Management.*

9. Helton, J. C., J. D. Johnson, and W. L. Oberkampf. 2004. An Exploration of Alternative Approaches to the Representation of Uncertainty in Model Predictions, *Reliability Engineering and System Safety*, 85 39-71.

10. Oberkampf, W. L., and J. C. Helton. 2005. Evidence Theory for Engineering Applications, Chapter 10 of *Engineering Design Reliability Handbook*, Nikolaides, E., D. M. Ghiocel, and S. Singhal, eds., CRC Press.

11. Dougherty, E. R. 1990. *Probability and Statistics for the Engineering, Computing, and Physical Sciences*, Prentice Hall.

12. Ferson, S. 2004. *Dependence in Probabilistic Modeling, Dempster-Shafer Theory, and Probability Bounds Analysis*, SAND2004-3072.

Notes

i. Sometimes the likelihood of attack is expressed as probability, P_A, instead of a frequency, f_A. Use of P_A can cause problems if the likelihood of an attack is not small. P_A depends on the time of interest. Usually, the time of interest is a year. P_A can be calculated from f_A, assuming that f_A is the parameter for an exponential distribution. The probability that the scenario occurs *one or more times* within time T is $P_A(T) = 1 – \exp(-f_A T)$ which approaches 1 for large $f_A T$. It is sometimes stated that f_A in units of per year is the probability over a time period of one year; this is true only if $f_A T << 1$, since $P_A(T) \approx f_A T$ for small $f_A T$, and for T equal to 1 year, $P_A(1)$ is numerically equal to f_A. Consider a situation where f_A is not small, such as attacks against U.S. military in Iraq, which has a frequency on the order of 1,000 per year. The probability of the event occurring *one or more times* over a time period of a year is $P_A(1) = 1 – \exp(-1{,}000*1)$ which is essentially 1. For estimating risk, we wish to weight the consequence by the likelihood of the initiating event. Using P_A of 1 instead of using f_A of 1,000 will significantly underestimate the risk. For these reasons, we quantify the initiating event as a frequency.

ii. P_E is the probability that security system defeats the attack. Therefore, $1 – P_E$ is the probability that the attack is successful.

iii. The name probability is used for two different concepts. The value PE is a probability in the classical, or objective, sense; the number of times an event occurs divided by the number of trials in the limit as the number of trials is infinite. The uncertainty in the value P_E (due to insufficient information to calculate the classical probability) is probability in the subjective or Bayesian sense, and it represents our state of knowledge about the likelihood of the value P_E. Both concepts obey the Kolmogorov axioms that mathematically define a probability measure.

iv. Using probability as the measure of uncertainty, $L_i(c)$ is the probability that c is exceeded for scenario i. Using belief/plausibility as the measure of uncertainty, we conservatively evaluate $L_i(c)$ using the plausibility that c is exceeded. [Reference 5]

v. To be precise, if the focal elements are singletons, belief/plausibility both become probability. If the focal elements are nested, belief/plausibility become necessity/possibility, respectively.

vi. Yager addresses the more general situation where the evidence is also on fuzzy sets. [See Reference 6]

vii. As the scenario evolves, the adversary may alter the scenario during both the planning and attack phases. This is not addressed in this paper.

viii. The scenario(s) evaluated in the defender model are identified using the adversary model as subsequently discussed.

ix. Noninteraction is discussed in Appendix A.

x. It is not required that PE and C be modeled using probability as the measure of uncertainty; for this example they are modeled probabilistically to illustrate that variables with a probability measure can be convoluted with variables with a belief/plausibility measure, since probability is a special case of belief/plausibility. In this example, the scenario is well defined so that the uncertainties in the performance of the security system and in the consequence are purely aleatory. For example, uncertainty in PE is dominated by the time for the guard force to respond given detection which depends on the random distribution of guards during the day. Uncertainty in C is dominated by the weather for a scenario involving release of a toxic chemical.

xi. The abscissa is not to scale in Figure 5.

xii. The curves in Figure 8 are the belief that the frequency will not exceed the indicated value. For an event A, Belief(A) = 1 – Plausibility$(\overline{A})$ where $\overline{A}$ is "not A", so the Belief of "not exceeding frequency f" is one minus the Plausibility of "exceeding frequency f."

xiii. Consideration of consequences that are difficult to evaluate numerically, such as "fear in the populace" can be addressed using a linguistic approach similar to that subsequently described for the adversary model.

xiv. Mitigation is considered as $C_{ij\ \mathrm{Mitigation}}$ instead of $C_{ij} * P_{ij\ \mathrm{Mitigation}}$ where $P_{ij\ \mathrm{Mitigation}}$ is some sort of probability for mitigation. Mitigation can change the likelihood distribution for consequence instead of lowering the unmitigated consequence likelihood distribution by a multiplicative factor.

xv. Here, it is assumed that if a scenario is detected during the formulation stage, the defender can bring sufficient resources to bear to stop the scenario.

xvi. That is, the adversary is not concerned with the precise likelihood of each variable of concern, such as "the probability of being detected" being less than 0.01. They focus on "we believe we are not likely to be detected" where not likely is ill-defined (a fuzzy set) but is understood to mean a low value (below on the order of 0.01). The decision is based on all variables of concern being acceptable to the adversary. The emphasis is on the variables of concern and how they interact rather than a precise numerical evaluation of these variables. Since the adversary has a choice, if all variables of concern are not acceptable for a particular scenario, the adversary will select another scenario.

xvii. Since both the evidence and the rules are at the fuzzy set level, and we do not have the fuzzy sets defined in terms of degrees of membership, the convolution is as if the fuzzy sets were crisp. The fuzziness of the sets is considered in the assignment of evidence, not in the convolution process.

xviii. The rule base is a form of approximate reasoning since it uses fuzzy sets.

xix. For linguistic random variables, the rule base is the algebra for convolution.

xx. If the adversary actually used this linguistic evaluation tool to assist in the selection of scenarios, the adversary would rank by belief. This is evident in exercises conducted by members of military special forces acting as a surrogate adversary; unless they *believe* that a scenario has high certainty of success, they will discard this scenario and chose another one with less uncertainty.

xxi. To be precise, X is the range for its corresponding random variable. In the remainder of this discussion, reference to the random variable X means the range for X. The set contains all possible unique outcomes for the random variable. The elements of the set are mutually exclusive.

xxii. <> denotes a tuple and {} denotes a set; a tuple is an ordered collection and elements can be repeated, a set is an unordered collection and elements cannot be repeated. Uppercase is used for a random variable and lowercase is used for a value of the random variable; for example, X is a random variable and x is a specific value for X.

xxiii. If the random variables X and Y are probabilities, combinations of these variables use the mathematics of a probability measure. For example, $X \cup Y = X + Y - X \cap Y$. If X and Y are mutually exclusive $X \cap Y = 0$; if X and Y are independent $X \cap Y = X*Y$.

xxiv. For example let X = {a, b, c} and let event A = {a, b} and event B = {b, c}. A and B are not mutually exclusive since both contain b. A subset with only one element is called a singleton. Singleton events are mutually exclusive.

xxv. For a finite set sup (supremum, or least upper bound) is max, and inf (infimum, or greatest lower bound) is min.

xxvi. As discussed earlier, here we are dealing with discrete sets. A probability measure requires that the probability of two disjointed events be the sum of the probabilities of each event. Since the elements of the set are mutually exclusive outcomes, the probability of any event defined on the set is the sum of the probabilities of its constituent outcomes.

xxvii. If we have defined a random variable on the sample space, the random variable can be viewed as transforming the sample space to the reals, and the range of the random variable can serve as a surrogate sample space. [See Reference 11.] Therefore, X can be a random variable (a sample space on the reals) for which π specifies a possibility distribution for the values of the range of the random variable.

xxviii. A binary relation is defined as a subset of the Cartesian product X x Y. For example, if X = {a, b} and Y = {p, q} then X x Y = {<a, p>, <a, q>, <b, p>, <b, q>} and R = {<a, p>, <a, q>, <b, q>} is a binary relation on X x Y.

xxix. The requirement that $m(A \times B) = m_x(A)*m_Y(B)$ means that for any focal elements A in X and B in Y, there is a focal element in X x Y formed by A x B with degree of evidence equal to $mx(A)*m_Y(B)$. The requirement that m(R) = 0 for all $R \neq A \times B$ means that any focal element in X x Y is a Cartesian product of focal elements in X and Y.

xxx. In possibility theory, another type of noninteraction is defined using a minimum operation. [See References 2 and 4.]

9/11 Families, NTI Launch Campaign to Prevent Nuclear Terrorism

Families of September 11 (FOS11) and the Nuclear Threat Initiative (NTI) in September 2006 distributed three new television public service announcements (PSA) to every broadcast and cable television station in the United States urging citizens to join in supporting efforts to prevent nuclear terrorism.

The announcements are part of a national public education campaign to raise awareness of the threat of nuclear terrorism and practical steps that can be taken to prevent it. The campaign urges citizens to take immediate action by calling for a dramatic acceleration of global efforts to lock down nuclear weapons and materials and by joining the Safer World Action Network, a community of citizens that has come together to help reduce these dangers.

Members of Families of September 11 were on Capitol Hill in September visiting with key members of Congress to discuss the campaign and distribute related materials, including the "Securing the Bomb" report, an annual report by Harvard experts analyzing the security of nuclear materials and weapons around the world and recommending steps to reduce the threat. The nonpartisan project has a number of high-profile supporters, including NTI Co-Chair Ted Turner and former Senator Sam Nunn; board members of Families of September 11; and 9/11 Commission Chair and Co-Chair Thomas Kean and Lee Hamilton.

In its initial report, the 9/11 Commission recommended an all-out effort to secure weapons of mass destruction, but in its final report card issued last year, the Commission gave the government a D for its progress so far. The joint public education campaign is named and focused on Turning the D into an A.

Components of the campaign include:

- Three public service announcements: "Protect America," which features three Families of September 11 Board members; "Scenario," which shows terrorists stealing nuclear weapons materials, as well as some of the ways it can be protected; and "Coming Together," featuring Kean and Hamilton. The PSAs can be viewed at www.saferworld.org.
- The PSAs direct citizens to a toll free phone number (800/336-0035) and a comprehensive Web site — www.saferworld.org.
- Nationwide public meetings and screenings of the nuclear terrorism docudrama "Last Best Chance" to encourage citizens to learn more about preventing nuclear terrorism. (For more about the film, visit www.lastbestchance.org).
- Learning materials to be used by leading educators to teach about nuclear threats. The educational packet includes resource books, a self-guided tutorial on nuclear threats, and other multi-media resources and is being provided to professors nationwide.

The project is also supported by the Carnegie Corporation of New York, the Toledo Community Foundation and donations from concerned citizens, including Dick and Fran Anderson of Ohio.

New Mexico Issues Permit For Remote-Handled Waste at WIPP

U.S. Department of Energy (DOE) announced in October 2006 that the New Mexico Environment Department (NMED) issued a revised hazardous waste facility permit for DOE's Waste Isolation Pilot Plant (WIPP) in Carlsbad, New Mexico. The revised permit enables WIPP to receive and dispose of remote-handled (RH) transuranic (TRU) radioactive waste currently stored at DOE clean-up sites across the country. WIPP expects to receive its first RH-TRU waste shipment in the coming months, as soon as the regulatory approvals are obtained.

Since opening in 1999, more than 83,000 containers of contact-handled TRU waste have been safely disposed in WIPP's half-mile deep repository. WIPP was designed for the safe disposal of both contact-handled and remote-handled TRU waste. Central to the permit issued in October is removal of the ban on disposal of remote-handled TRU waste at WIPP. Other revisions to the permit include alternate methods for analyzing wastes prior to shipment to WIPP, increased container storage areas aboveground, more efficient methods for monitoring volatile organic compounds in the repository, a new dispute resolution process, and an e-mail notification system to inform the public of various permit-related activities.

WIPP is the world's first repository for the permanent disposal of defense-generated transuranic radioactive waste left from research and production of nuclear weapons. Located in southeastern New Mexico, twenty-six miles east of Carlsbad, WIPP facilities include disposal rooms excavated in an ancient, stable salt formation, 2,150 feet (almost one-half mile) underground. Waste disposal began at WIPP on March 26, 1999.

DOE's Rocky Flats Cleanup Site Named 2006 Project of the Year By Project Management Institute

The U.S. Department of Energy (DOE) announced in October 2006 that the Project Management Institute (PMI) has awarded its 2006 Project of the Year to DOE's Rocky Flats Environmental Technology Site. The award was presented to DOE contractor Kaiser-Hill, LLC during the PMI Global Congress Dinner 2006 on Saturday, October 21, 2006, in Seattle, Washington.

DOE and Kaiser-Hill successfully partnered in a ten-year effort to complete the largest, most complex environmental cleanup project in United States history and converted an environmental liability into a community asset, completing the project nearly fifty years and $30 billion below initial estimates. The majority of the 6,200-acre site will be transferred to the U.S. Interior Department in the coming years and will become a national wildlife refuge. DOE has closed five sites including Rocky Flats in fiscal year 2006 and is on track to safely turnover an additional twelve between FY2007-FY2009.

The Rocky Flats Closure Project included the following:

- Removed more than twenty-one tons of weapons-useable nuclear materials
- Decontaminated and demolished 800 structures, comprising more than 3 million square feet
- Drained 30,000 liters of plutonium solutions
- Dismantled and removed more than 1,450 contaminated production glove boxes and 700 tanks
- Stabilized and packaged 100 tons of high-content plutonium residue
- Performed environmental cleanup actions at 130 sites
- Dispositioned millions of classified items and excess property
- Safely shipped more than 600,000 cubic meters of radioactive waste – enough to fill a string of railcars 90 miles long

The PMI Project of the Year is one of the world's most prestigious project management awards and recognizes and honors the accomplishments of the winning project team for superior and exemplary project management.

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