Summary and Briefings from the
Stanford-China Workshop on Reducing Risks of Nuclear Terrorism
Stanford Center at Peking University
June 6-7, 2016
Summary and Briefings from the Stanford – China Workshop on Reducing Risks of Nuclear Terrorism

Held June 6-7, 2016 at the Stanford Center at Peking University
Beijing, China

Abstract

A collaborative project engaging researchers from the Center for International Security and Cooperation at Stanford University and several Chinese nuclear organizations focused on the response to nuclear terrorism threats. A goal of the research was to identify prospective joint research initiatives that might reduce the global and regional dangers of such threats. Initiatives were identified in three technical areas: interdiction of smuggled nuclear and radiological materials; nuclear forensics; and countermeasures to radiological (“dirty bomb”) threats. Application of the methodologies of systems and risk analysis to the framing and initial assessment of these areas was emphasized in the project. The workshop summarized in this report brought together the analysis work from this project and related efforts by both Chinese and U.S. analysts.

Compiled by
Elliot Serbin and Larry Brandt
Center for International Security and Cooperation
Stanford University
September 2016
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Summary and Briefings from the
Stanford – China Workshop on Reducing Risks of Nuclear Terrorism

Workshop Summary

Background
The Nuclear Risk Reduction program at the Center for International Security and Cooperation (CISAC) at Stanford University seeks to reduce global nuclear dangers through international technical cooperation. The growing threats of nuclear terrorism and proliferation in East Asia have made engagement with China a critical aspect of this work. Such engagements support China’s efforts to improve its nuclear security culture and to exercise more effective regional leadership in controlling and responding to nuclear threats. In addition, collaboration between China and the U.S. will build the technical protocols and relationships that can make joint responses to international nuclear events more effective. This type of nuclear cooperation has been recognized and endorsed as a vital contributor to global security in recent Nuclear Security Summits by the leaders of both China and the U.S.

Over the past two years, Stanford CISAC researchers and nuclear experts in China have together focused on a project that addresses the threat of nuclear terrorism. This project has examined technologies and systems that can respond to terrorist radiological or nuclear operations that are underway. Several key research areas that could contribute to more effective responses have been identified. Options for future collaborations in these areas have also been developed. Initial studies were performed on selected research topics to frame the problems and to highlight pathways for future work. The purpose of the workshop summarized in this paper was to share the results of this project and related work being pursued in China and the U.S. It was held on June 6-7, 2016 in Beijing at the Stanford Center at Peking University.¹

Project Description
A major aspect of the current project has been a series of engagements between Chinese and U.S. technical experts resulting in the designation of three principal research areas that offer promise for longer-term collaborations. These choices were based on discussion of a range of terrorist nuclear and radiological scenarios. The selection criteria including the level of mutual interest, potential risk reductions due to technical countermeasures, and the ability to share relevant information. The resulting principal research areas are:

¹The primary support for the execution of this workshop and for several of the studies briefed in the workshop was provided by the Project on Advanced Systems and Concepts for Countering WMD (PASCC) administered by the Naval Postgraduate School. In addition, the Carnegie Corporation of New York and the MacArthur Foundation have provided critical support for portions of the project and for the continuing engagements with China’s nuclear community.
Each is discussed in greater detail below. One session of the final workshop was devoted to each of the three areas.

Within the research areas, several collaborative analysis activities were pursued. First, discussions between Chinese and U.S. experts identified questions of mutual interest in each area. This was assisted by orientation briefings from both sides in the project kickoff workshop held in Beijing in June 2014. Second, further engagements, including contributions of a Visiting Scholar from the China Institute for Applied Physics and Computational Mathematics (IAPCM) generated a broader set of technical collaboration options and strategies. Finally, initial studies were performed on selected questions in each research area. The results from each of these analysis activities, along with relevant ongoing work in China and the U.S. provided the technical content of the final workshop.

Principal Research Areas

**Interdiction of Smuggled Nuclear Materials:** The detection, characterization, and interdiction of nuclear and radiological materials that are outside of administrative controls has received growing attention worldwide over the last decade. The technologies and architectures associated with this security challenge was a major focus of the team of researchers working at Stanford during the project. Two classes of scenarios, one in which the smuggled material passes through a choke point (e.g., port of entry, transit terminal, secure area portal), and another in which the material is hidden or transiting within a much larger search area, were considered. The technical tools and operational approaches for these two classes of scenarios are very different. Initial systems framing and analysis were completed in each area. The research suggested collaboration strategies and specific technical options that could improve mutual capabilities in this area.

**Nuclear Forensics:** An effective nuclear forensics capability has been widely recognized as a vital tool in deterring and responding to possible terrorist actions. Current U.S. and international programs that can improve capabilities, increase confidence in the analysis process, and build human capital provide a starting point for considering future bilateral collaborations. Challenges facing China in its development of a robust and internationally recognized nuclear forensics capability were a major topic of discussion in the engagements in this project. Of particular interest was the role that analysis and modeling might contribute to this goal. In response to this question, an initial framing study that examined analytic elements of signature and database development was pursued as a part of this project. In addition, several nuclear forensics experts participated in the project to suggest directions in which bilateral collaboration might be useful. These new directions build upon the considerable progress that has already been made by China with the support of current U.S. and multilateral programs.

**Countermeasures to Radiological (“Dirty Bomb”) Threats:** Extensive systems analysis studies to understand the range of possible terrorist radiological attacks and to recommend programs to reduce the probability and impact of these attacks have been completed in the U.S. A key U.S. analyst in this area joined the research team late in the current project to provide insights into current findings and potential directions for future work.
Systems and Risk Analysis as a Collaboration Tool

Within the U.S. national security community, systems analysis and its variants (e.g., risk analysis, decision analysis, scenario planning, systems gaming) are primary tools in defense assessment and resource allocation processes. The concepts and tools of strategic decision analysis appear to offer significant benefits for collaborative international projects. More specifically, these tools provide ways to handle several important collaborative analysis problems. One is representation of uncertainties about future events (e.g., capabilities and intent of adversaries, future scenarios, physical and environmental factors). Another is the development of a diverse set of strategic alternatives that can broaden the perspective of the analysis. Finally, explicit value metrics are central to the process, allowing the consideration of differences in national values on the strategies chosen and on preferences for specific collaboration activities.

Recognition of the potential importance of systems analysis methodologies, along with the analysis skills of the U.S. team and the strategic analysis mission of CAEP/CSS, resulted in a decision to emphasize systems and risk analysis approaches in the project. The workshop briefings presented by the collaborative Stanford-China analysis team display a range of systems treatments, from high-level framing studies to more detailed systems modeling and Bayesian analysis formulations. These results are exemplary of the approaches used by analysis groups in major U.S. national security institutions and national laboratories. The initial work reported in this workshop was designed to explore the utility of such systems and risk analysis tools for broader application to Chinese and collaborative work.
Session #1

Interdiction of Smuggled Radiological and Nuclear Materials

Briefing 1: “Application of System and Decision Analysis for Port and Transit Radiation Detection”, ZHANG Songbai (Institute for Applied Physics and Computational Mathematics)

This study applies the tools of decision and risk analysis to frame key issues surrounding the use of technical systems, particularly those that use radiation detectors, in the discovery of illicit nuclear or radiological materials passing through ports or other transit facilities. The work first characterizes the challenges facing these detection architectures. It then outlines China and U.S. deployments and provides a qualitative assessment of their effectiveness based on reference to existing studies. The analytic focus of the work is the framing of detection system elements and uncertainties using a decision diagram format, followed by use of Bayesian network tools to begin further analysis. Possible strategies for technical collaborations are also developed.

Briefing 2: “Wide Area Search: A Central Challenge in Countering Nuclear Terrorism”, Jason Reinhardt (Stanford University and Sandia National Laboratories)

This work addresses the particularly difficult problem of the search for nuclear materials when their location is not well known within a large area. It begins with a taxonomy of search scenarios followed by a discussion of the physics and operational challenges associated with the mission. The many variants of wide area detection architectures are summarized. A maritime search example then provides a more specific context for the analysis. A decision diagram characterization and a notional Bayesian network model were developed for this exemplary case. Reasonable probability assessments were made to illustrate the relative quantitative value of several types of detection system enhancements. These included increased detector performance, more effective vehicle inspection operations, and improvements in vessel locating capability through surveillance and information sharing. The importance of vessel location knowledge was highlighted by these initial sensitivity study results.


This briefing reviews development of two algorithms for localization of a radioactive source within a fixed area – one algorithm for passive detection and the other for active detection. The performance of the algorithms is assessed by simulation against a variety of sources. Quantitative measures of location uncertainties provide estimates of the relative performance of the two algorithms under various conditions. Sensitivities of algorithm performance to background levels and to source strength and shielding are also assessed.
Session #1; Briefing 1: “Application of System and Decision Analysis for Port and Transit Radiation Detection”, ZHANG Songbai (Institute for Applied Physics and Computational Mathematics)
Session #1; Briefing 1: ZHANG Songbai (cont.)

Structuring the overall Counter Rad-Nuc Terrorism

- Two key technical problems
  - Two key technical problems
    - Shielding
      - Imaging
      - Passive + active
  - Wide area searching
    - Optimization searching
    - Data fuse analysis

Current radiation detection system deployed at ports and transits

- U.S. deployment
  - Analyze specific operational set-ups that facilitate opportunities for detection

Current radiation detection system deployed at ports and transits

- China Deployment
  - Processing of U.S.
    - Policy goal: Screening of all incoming containers
    - Lockdown all the materials
      - Second line of defense of DoE/E PAAS
      - Security and Prosperity Partnership (SEP)
      - 10/14 initiative (IEP)
    - Understand movement of nuclear material
      - T-V project (25/74)
      - Intelligence on target
      - Provenance (trace of custody)
      - Automated targeting systems (CATS)
      - Materials Protection and Safeguarding Initiative (MPSI)

- Strategy of China
  - Policy goal: unfolding from open source
  - Focus on inspection of suspected materials, assisted by radiation detection
  - Physical protection and radiation sources (DTrace)
    - MPSI
    - Radiation sources ID
  - Radiation monitoring at key points of custody
    - Material production
    - Transit
    - Radioactive resources
Session #1; Briefing 1: ZHANG Songbai (cont.)

Current radiation detection system deployed at ports and transits

- Involved departments for port detection
  - U.S.: Department of Homeland Security
  - China: Ministry of Public Security

Qualitative assessment of current detection system

- Radiation passive detection (scanning)
  - consisting of large-area gamma-ray detectors (usually plastic scintillation detectors and neutron detectors (He-3 detectors in polyethylene moderator material)
  - allow the passive detection of nuclear materials or other radioactive materials to be detected in cargo containers or trucks entering or leaving a port.

- Radionuclide Identification (screening)
  - identify the type of radionuclide that triggered an alarm
  - identify the isotopic composition
  - analyze the characteristic gamma spectra or neutron spectra by embedded sensitive detector

Qualitative assessment of current detection system

- Alarm was triggered by:
  - U.S.: Litter, Ceramics/Tile/toilets, televisions, metal, scouring pads, refractory material, fertilizer/potash, earth, Medical sources
  - China (from 2007-2011):
    - scrap metals, hardware waste, mineral products (244+13)
    - Th: 998Bq, Co: 19g (3)

Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>U.S.</th>
<th>China</th>
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<tr>
<td>Gamma energy range</td>
<td>20keV-3MeV</td>
<td>30keV-3MeV</td>
</tr>
<tr>
<td>Gamma typical resolution</td>
<td>≤7.5 % FWHM at 662 keV</td>
<td>≤8.5 % FWHM at 662 keV</td>
</tr>
<tr>
<td>Minimum detectable amounts of materials</td>
<td>U-235: 32g U-238: 480g, Pu-239: 0.9g, Co-60 1.2Ci (source velocity 3nm/h)</td>
<td>Co-60 2.5×10^6/s alarm 80% Cf-252 2×10^6/s alarm 90% (2.2m/s unshielding)</td>
</tr>
<tr>
<td>False alarm rate</td>
<td>&lt;0.1%</td>
<td>&lt;0.1%</td>
</tr>
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Framing analysis for the cost-effectiveness of detection system

Factors

- Threat
- Detection
- Metrics of capability

Framing analysis for the cost-effectiveness of detection system

Top level decision diagram

- Decision of the modeling
- Decision of accuracy
- Decision of Damages associated
Session #1; Briefing 1: ZHANG Songbai (cont.)

Framing analysis for the cost-effectiveness of detection system

- Decision strategy table
  - Strategic issue: Threat with detection & detection capacity (level 1: software)
  - Candidate solutions: Cost, technical, operational, etc.
  - Decision matrix: Cost-effectiveness
  - Decision analysis: Cost, technical, operational, etc.
  - Decision recommendations: Cost, technical, operational, etc.

Framing analysis for the cost-effectiveness of detection system

- Simple example
  - Detection capability: status quo (impl-1-impl-2-impl-3)
  - Efficient: Status quo (impl-1-impl-2-impl-3)
  - Cost: status quo (impl-1-impl-2-impl-3)

- Best decision: impl-2
- Detection is key factor, need to tradeoff between efficient and cost.

Ideas of possible collaboration on this topic

- Possible Collaboration
  - Immediate capability on identifying the threat from the scenario
  - Threat assessment
  - High-risk detection or low benefits detection material
  - Active inspection method & its impact
  - Decision support
  - Operational conditions
  - Information exchange

Conclusion

- We present a preliminary framing method to
  - Set up the scope of decision problems and the fundamental objectives to evaluate potential solution.
  - Identify the uncertainties and their relationships
  - Generate the strategy table to address identified decision problems.
  - Construct a top level of decision support model.

- The top level of decision diagram/model might be helpful to assess the cost-effectiveness for port and transit detection system.
- Although different countries have different strategy to counter nuclear terrorism, the similarly Detection Architecture are adopted to detect and interdict the illegal diversion of Rad-Nuc Materials.

Acknowledgement

- Siegfried Hecker, Larry Brandt and Jason Reinhardt: earnest guidance, greatest patience.
- Isabella Uria and Liu Wenhao: kindest helps.
- Elisabeth Paté-Cornell, Ronald Howard, Carole Mawson and Robyn Lockwood: let me in their classes.

- Hu Si, Tian Dongfeng, Wu Jun, Xie Dong

Thanks for your attention!
Session #1; Briefing 2: “Wide Area Search: A Central Challenge in Countering Nuclear Terrorism”, Jason Reinhardt (Stanford University and Sandia National Laboratories)

Wide Area Search: A Central Challenge in Countering Nuclear Terrorism
Jason Reinhardt
reinhardt@stanford.edu
Stanford Center at Peking University (SCPKU)
June 6-7, 2016

Phases of Systems Analysis

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Outline

- The Wide Area Search Problem
- An Example Scenario and Notional Model
- Example Analysis
- Conclusions and Next Steps

Checkpoints, ports, and transit centers offer several operational advantages.

- Limited engagement geometries
- Operationally controlled environments
- Extensive support infrastructure
- Inspection of large volumes of people, vehicles, and cargo

Wide Area Search often has none of these advantages.

Classes of Wide Area Search Problems

Physics limits the effectiveness of radiation detection systems.

In free air, maximum detection distance is a few hundred meters.

Taken from a presentation by Lund and Reinhardt, SNL.
Session #1; Briefing 2: Jason Reinhardt (cont.)

Physics limits the effectiveness of radiation detection systems.

Many architecture strategies for wide area search have significant limitations.
- Ubiquitous Detection
  - Capital intensive, costly
  - False/Nuisance alarms frequent
- Stand-Off Detection
  - Physics limit feasibility at long distances
  - Operationally impractical in some cases
- Boundaries and Checkpoints
  - Difficult to establish effective borders
  - False/Nuisance alarms frequent
- Patrol Operations
  - Labor intensive, costly
  - Possibly low probability of encounter
- Responsive Search
  - Can be inefficient for large areas
  - Challenging in low information situations

Selected Architecture Components

Options for Wide Area Search

A Notional Model: Caution!
- The model is meant to provide an example for the purposes of demonstration of the analysis.
- The data contained in the model are intended only to be suggestive of possible performance.
- The structure of the model is intended to be an “initial draft” and must be revised as collaborations continue.

Example Scenario: Focus Area
Session #1; Briefing 2: Jason Reinhardt (cont.)

Example Scenario: Maritime Wide Area Search

- Assumptions:
  - Radiological source is missing and possibly in transit to target
  - Source is aboard an unknown vessel
  - Vessel believed to be traveling in coastal waters
  - Goal is to maximize probability of interdiction

- Questions:
  - What is the baseline probability of interdiction?
  - How can it best be improved through collaborative development?
    - Information sharing
    - Improved area monitoring
    - Improved detection systems
    - Training response forces

Wide Area Radiation Detection

- Assume search teams are equipped with a 4"x4"x16" (100mm x 100mm x 400mm) NaI(Tl) detection system, measuring gross gamma counts.

- Detection goals
  - Find vessel in coastal ocean,
  - board it, and
  - search it to locate the source.

- Background radiation fluctuates around an expected spectra.

A Notional Model: Influence Diagram

A Notional Model: Implementation

A Notional Model: Implementation

A Notional Model: Intuition Check
Session #1; Briefing 2: Jason Reinhardt (cont.)

Detector Enhancement Alternatives

**Alternative 1:**
- Background Suppression
- E.g. Collimation
- Lowers background levels
- Improves signal-to-noise

**Alternative 2:**
- Improved Discrimination
- E.g. Spectral Identification
- Lowers effective alarm threshold
- Rejects false and nuisance alarms

Comparing Alternative Enhancements

**Alternative 1:**
- Background Suppression

**Alternative 2:**
- Improved Discrimination

Enhancements to the detection system provide modest gains to overall system performance.

- Costs and achievable performance can be informed by laboratory experiments and further modeling.

Maritime Operational Enhancement Alternatives

**Alternative 1:**
- Improved monitoring of maritime commons
  - E.g. Radars, patrol
  - Identifies and locates vessels of interest
  - Improves search efficiency, probability of locating vessel

**Alternative 2:**
- Improved vessel inspection techniques
  - E.g. Training on inspection
  - Improves operational effectiveness
  - Improves probability of finding contraband

Comparing Alternative Enhancements

**Alternative 1:**
- Improved monitoring of maritime commons

**Alternative 2:**
- Improved vessel inspection techniques

Improvements in inspection operations do not yield significant improvements in performance.

- Large improvements in inspection performance are overwhelmed by gains in improvements in locating the vessel.
- Technical improvements to the detection system are also less effective than improvements to locating the vessel.
Session #1; Briefing 2: Jason Reinhardt (cont.)

Information Quality Enhancement Alternatives

- E.g. Radars, patrol
- Identifies and locates vessels of interest
- Improves search efficiency, probability of locating vessel

- E.g. Crisis Co-operation
- Ensures the best possible knowledge of the threat
- Improves ability to locate the vessel quickly

Comparing Alternative Enhancements

- Alternative 1: Improved monitoring of maritime commons
- Alternative 2: Information Sharing to Improve Intelligence

- Intelligence Quality
- Probability of Interdiction

Enhanced maritime monitoring and information sharing approaches may yield similar gains

- Both yield similar improvements to interdiction probability
- Improved monitoring provides higher maximum performance
- Next steps of analysis may focus on:
  - Possible improvement options (e.g. improved maritime tracking, cooperative monitoring agreements, etc.)
  - Expected level of improvement
  - Cost per unit of improvement

Conclusions

- Wide Area Search presents one of the most challenging problems for countering nuclear terrorism.
  - Depending on the environment, high clutter and high nuisance alarm rates present significant operational challenges.
  - Radiation detection, while important, may have a limited role due to physics and operational considerations.
  - A mix of strategies is often required, and is often dictated by the specific scenario.

- Under the assumptions and constraints of the example scenario and model in this presentation:
  - Enhancements to the ability to locate the vessel provide the best opportunities for improving interdiction probability.
  - Improved maritime surveillance (e.g. radars)
  - Increased patrols
  - Information sharing
  - Cooperative monitoring of the commons
  - Improvements to detection equipment or vessel inspection operations yield only limited performance enhancement.

Next Steps

- With this analysis as an example and starting point, collaborative efforts could include:
  - Refinement and enhancement of model structure
  - Development of enhanced sub-models and data
  - Re-assessment of possible technical and operational solutions
  - Development of additional models for additional architecture problems

Image Credits and References

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- http://en.wikipedia.org/wiki/Arx1e3e-scoutball
- NanoS_Nanopore_Corporation
**Two Possible Algorithms for Radioactive Sources Locating by Radiation Detection**

China Academy of Engineering Physics, Center for Strategic Studies

Zhu Jianyu
2016, 6

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**Outline**

1. Study background
2. Scenarios and Models
3. Location estimation by passive detection
   3.1 Arithmetic
   3.2 Simulation and discussion
   3.3 Limitations
4. Location estimation by active detection
   4.1 Simple treat of count
   4.2 Maximum likelihood method
5. Conclusion

---

**1 Study background**

- For the purpose of nuclear material security and reduce the risk of nuclear terrorism, it is important to develop technologies for rapidly and accurately locating the radioactive material.
  - To find the hidden of lost radioactive material
  - To find the “dirty bomb” or “dispersion source”, before terrorist incident takes place.

**2 Scenarios and Models**

- Scenarios and simplification
- Radiation source
- Medium and Detectors

---

**2.1 Scenarios and simplification**

Possible scenarios:
- Building (Outdoor, City...)
- People (Crowd, Platform, Football game, Concert...);
- Vehicle (Parking area, Port...);

Simplified as:
- Radioactive source in a uniform medium. The detectors surround the medium.

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**2.2 Radiation source**

Different kinds of common used sources with security risks are considered.

- Neutron source

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Session #1; Briefing 3: ZHU Jianyu (cont.)

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</tr>
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</table>

<table>
<thead>
<tr>
<th>Source</th>
<th>134Cs</th>
<th>133Ba</th>
<th>137Ba</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isotopes</td>
<td>5.93E10</td>
<td>1.21E7</td>
<td></td>
</tr>
</tbody>
</table>

Medium and detectors

- Uniform absorption medium
- The detector are surrounded
- The source is within the area

The intensity for each detector could be written as:

\[ \alpha = \frac{e}{\pi R^2} \frac{1}{t} \frac{I}{\text{medium absorption}} \]

For active detection, additional sources are introduced in Z direction (drones fly past the area in the sky).

3 Location estimation by passive detection

3.1 Arithmetic

From the relation function:

\[ f(x, y, L) = \frac{C}{4 \pi L} \frac{1}{(x-x_i)^2 + (y-y_i)^2 + L^2} \]

We have:

\[ \frac{1}{(x-x_i)^2 + (y-y_i)^2 + L^2} = \frac{e}{4 \pi r} \]

Regression by non-linear LS (Least Squares) method

Linearization around \([x_0, y_0, L_0]\) to the form:

\[ f(x, y, L) = f(x_0, y_0, L_0) + \frac{\partial f}{\partial x}(x-x_0) + \frac{\partial f}{\partial y}(y-y_0) + \frac{\partial f}{\partial L}(L-L_0) \]

write as:

\[ \begin{pmatrix} \frac{\partial f}{\partial x} \\ \frac{\partial f}{\partial y} \\ \frac{\partial f}{\partial L} \end{pmatrix} = \begin{pmatrix} x-x_0 \\ y-y_0 \\ L-L_0 \end{pmatrix} \]

Iterative process

The location and intensity would be solved iteratively, with condition of convergence.

\[ \begin{pmatrix} x_1 \\ y_1 \\ L_1 \end{pmatrix} = \begin{pmatrix} x_0 \\ y_0 \\ L_0 \end{pmatrix} + \frac{1}{\frac{\partial f}{\partial x} x_0 + \frac{\partial f}{\partial y} y_0 + \frac{\partial f}{\partial L} L_0} \begin{pmatrix} \frac{\partial f}{\partial x} \\ \frac{\partial f}{\partial y} \\ \frac{\partial f}{\partial L} \end{pmatrix} \]

An example with \(I=3.05\) Bq, \(x=17.5\) m, \(y=26\) m.

Four interactions are done before convergence.
Session #1; Briefing 3: ZHU Jianyu (cont.)

In order to understand the uncertainty of the estimation, repeated experiments were carried out. The average distances between each source and estimation are counted.

10000 times, the average distance is less than 1.6 m for 50m*50m square area.

3.3 Limitations

3.3.1 Background radiation

The background radiation in atmosphere would cover the radiation signatures or would cause fault alarm.

3.3.2 Material with weak radiation or shielding

<table>
<thead>
<tr>
<th>Isotopic Abundance</th>
<th>Neutron Yield (g/g)</th>
<th>Metal Mass (kg)</th>
<th>Dioxide Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WSU</td>
<td>0.00%</td>
<td>93%</td>
<td>5.9%</td>
</tr>
<tr>
<td>HEU</td>
<td>0%</td>
<td>80%</td>
<td>50%</td>
</tr>
<tr>
<td>Np</td>
<td>0.73%</td>
<td>99.27%</td>
<td>0.014</td>
</tr>
<tr>
<td>Am</td>
<td>1.7 x 10^6</td>
<td>1.9 x 10^7</td>
<td></td>
</tr>
<tr>
<td>WPFu</td>
<td>9.1 x 10^4</td>
<td>5.8 x 10^6</td>
<td>2.2 x 10^6</td>
</tr>
<tr>
<td>RGfu</td>
<td>1.1 x 10^6</td>
<td>1.5 x 10^6</td>
<td>4.2 x 10^7</td>
</tr>
</tbody>
</table>

4 Location estimation by active detection

When active detection is used, the interrogation source would cause fission or other nuclear reaction on hidden nuclear material with neutron or gamma radiations.

For cargo monitoring, if active detection is applied, the possibility of catching the nuclear material would be enhanced.

4.2 Maximum likelihood method

Find the location from where the likelihood gains its maximum

The likelihood function with Maxwell neutron spectrum

\[ P_{\text{f}}(r(x, y), E) = \frac{2}{\pi^2} \int_{0}^{\infty} P(E) \frac{1}{(2E)^{3/2}} \exp \left( \frac{-E}{2E} \right) \delta \left( x - x_0 \right) \delta \left( y - y_0 \right) \delta \left( E - E_0 \right) \]

Bulk likelihood function could be written respect to \((x, y)\)

\[ \ln L = \sum P_{\text{f}}(r(x, y)) \]

\[ \text{Maximum Likelihood} \]

4.1 Simply treat of count

- For mono-energy neutron

  Estimate the location by finding the location with minimal variance between detection and calculated time intervals

\[ \psi(x, y) = \sum \left( \psi(x, y) - \psi(x_0, y_0) \right) \]

  where,

\[ \psi(x, y) = \sum (\delta(x) - \delta(x-x_0)) \delta(y-y_0) \]

- But for fission neutron, sometimes the calculation would be non-convergent.
5 Conclusion

- It is possible to locate the radioactive source by radiation detection.
- **Passive detection** could be useful, but **TWO** condition must be meet:
  - The radiation is stronger than the background.
  - The source is not sufficiently shielded.
- Under the condition that the passive method is invalided, if it is possible, the **active method** could find the material more effective, especially when prior knowledge is used.
Session #2

Nuclear Forensics

**Briefing 1:** “Tabletop Exercise Nuclear Incident Scenario – Technical Insight”, ZHANG Jiaqi (China Institute of Nuclear Information and Economics)

This briefing summarizes a recent tabletop exercise attended by several Chinese government organizations that analyzed a scenario involving the capture of illicit highly enriched uranium (HEU). The scenario hypothesized the discovery of HEU by the U.S. in the crash of an aircraft from Central Asia that had last landed in China. The scenario also involved a later discovery of HEU by China on a similar transport aircraft forced to make an emergency landing in Southern China. This tabletop explored China’s emergency response and technical forensics options. The role of international cooperation and responses to U.S. queries were also topics of discussion in the tabletop.

**Briefing 2:** “Confidence Building Activities to Support a Robust Nuclear Forensics Capability”, Sue Clark (Washington State University)

This briefing describes several essential elements in the development of a robust nuclear forensics capability. It begins by introducing the overall response to a nuclear event as outlined in the model action plan. Technical forensics are a key part of this plan. Confidence in forensics measurements depend on both good laboratory practices and good management practices. The use of IAEA reference samples in the validation of processes for Pu isotopic analysis was cited as one example of the discipline required in the development of high confidence processes. Tradeoffs among accuracy, precision, and speed depend on the nature of the nuclear event and are a critical consideration in the design of measurement processes. International exchanges can provide very useful support to the development of technical nuclear forensics expertise.

**Briefing 3:** “Human Capital Development for Nuclear Forensics”, Nathalie Wall (Washington State University)

This briefing begins by examining in greater detail the role of technical nuclear forensics capabilities in all aspects of the model action plan for nuclear events. The U.S. programs designed to develop and maintain the human capital needed to realize these capabilities are then reviewed. The undergraduate Nuclear Forensics Summer School at Washington State University is one example of an efficient approach to the development of technical nuclear forensics expertise.

**Briefing 4:** “Numerical Simulation Work on Nuclear Spent Fuel for Nuclear Forensics”, SU Jiahang (Center for Strategic Studies, China Academy of Engineering Physics)

This briefing describes initial studies that utilize models of reactor fuel isotopics to develop signatures that can be used in the forensics analysis of spent fuels. Initial modeling focused on a 5MWe air-cooled reactor and included isotopic sensitivities to burn-up range and cooling time.
Subsequent work applied factor analysis to the characterization of known spent fuel samples to confirm the ability of the methodology to determine reactor type, fuel composition, and burn-up. Application of factor analysis techniques increases the discrimination of sample analyses over what would be possible using just one or two characteristic isotopes.

**Briefing 5: “Development of Nuclear Forensics Capabilities – A Systems Framing Study”, Larry Brandt (Stanford University)**

This briefing summarized an initial systems framing study that identified ways in which modeling and analysis might support development of more effective nuclear forensics capabilities. The work highlights the importance of signature development and its database and analytic components. Differences between predictive signatures that utilize process knowledge and models as opposed to comparative signatures that require reference samples was reviewed. (The use of models as a basis for signature development is illustrated in Briefing 4 of this workshop session.) Modeling and analysis can fill in the gaps in national forensics databases that cannot be covered by sample collection or international data. The structure and processes for international information sharing following a nuclear event is another area in which analytical efforts would be useful.
Session #2; Briefing 1: “Tabletop Exercise Nuclear Incident Scenario – Technical Insight”, ZHANG Jaiqi (China Institute of Nuclear Information and Economics)

**Tabletop Exercise**

**Nuclear Incident Scenario**

Aircraft accidents reveal nuclear terrorist plot

**Technical insight**

2016.06.02

---

**Scenario introduction**

Emergency event 1 (aircraft crash @ U.S.)

*In late August, 2016, a U.S.-based international cargo express aircraft from China crashes on landing at Los Angeles International Airport.*

Aircraft fire, rescue, police response, crash site secured.

**Scenario**

Emergency event 1 (aircraft crash @ U.S.)

*aircraft’s flight plan: take off in Shanghai China, partially ruptured cargo container is discovered, heavily shielded container contains several smaller canisters*

**Scenario**

Emergency event 1 (aircraft crash @ U.S.)

*canisters contain metallic uranium (gamma detector), approximately 8 Kg, 75% U-235 (HEU)*

“experts” speculate a nuclear terrorist plot against U.S. a talk that this plane was seeking to smuggle nuclear weapons materials from a third country into U.S. by hiding it within a cargo shipped from China. none of these “experts” allege Chinese involvement but they call for cooperation.
Session #2; Briefing 1: ZHANG Jaiqi (cont.)

Scenario introduction

Emergency event 2 (aircraft crash @ U.S.)

- 3 days later
  - A second cargo plane makes an emergency landing in extreme weather at an airport on the coast of southern China.
  - Aircraft fire, rescue, police response, crash site secured.

Scenario

Emergency event 2 (emergency landing @ China)

- a non-U.S. cargo plane makes an emergency landing at an airport on southern China
- airport temporarily closed

(within hours after the emergency landing)
- aircraft's flight plan: refueling stop in Myanmar
- final destination U.S.
- heavily shielded containers are discovered
Session #2; Briefing 1: ZHANG Jaiqi (cont.)

Scenario

Emergency event 2 (emergency landing @ China)
- Press leak information: nuclear weapons material had been aboard
- Containers contain 12 Kg, metallic uranium, 75% U-235

Scenario & Technical Solution

U.S.'s concern:
- Whether China would inform U.S. that there was nuclear materials on this plane immediately?

Yes
- U.S. requires co-investigation immediately
- Trilateral conjoint analysis

No
- In a passive position immediately

Scenario & Technical Solution

Scene management
- Shielding container measurement
  - Cargo exam (suspect)
  - Hazard assessment (explosive, virus, radiation, etc.)
  - Cargo unpacking (shielding container)
  - Hazard assessment (explosive, virus, radiation, etc.)
- Container transportation (to lab)
- Scene release

Scenario & Technical Solution

Link of the two events
- Important to figure out the terrorist plot

<table>
<thead>
<tr>
<th>Event</th>
<th>Material</th>
<th>Abundance</th>
<th>Weight</th>
<th>Destination</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Metallic U</td>
<td>75% U-235</td>
<td>8 Kg</td>
<td>U.S.</td>
<td>Apr. 15 2016</td>
</tr>
<tr>
<td>2</td>
<td>Metallic U</td>
<td>75% U-235</td>
<td>12 Kg</td>
<td>U.S.</td>
<td>Apr. 18 2016</td>
</tr>
</tbody>
</table>

Scenario & Technical Solution

Graded Decision System
- Uranium content
  - Microcosmic morphology
- Valence & structure
  - Geological location
- Uranium isotopic composition

Scenario & Technical Solution

Regulation on the disclosure of information
- Emergency response:
  - Ministry of Public Security
  - Ministry of Environmental Protection
- Invite IAEA or other organization to participate in investigation/analysis/attribution
- Comparison analysis of materials from these two events
Session #2; Briefing 1: ZHANG Jaiqi (cont.)

Scenario & Technical Solution

summary

1. material origin
2. smuggle route
3. link of the two events

Scenario & Technical Solution

follow up discussion
“large port project” airport not included
cooperation between U.S. & China IAEA?
database sensitive information

Outlook

International cooperation

1. Technical collaboration
   Technical R&D
2. Building confidence
   Technical collaboration
   Communication
   Exercise

Thanks for your attention!
Session #2; Briefing 2: “Confidence Building Activities to Support a Robust Nuclear Forensics Capability”, Sue Clark (Washington State University)
Session #2; Briefing 2: Sue Clark (cont.)

Building Confidence

Certified Reference Materials (CRMs), Radioanalytical Methods, & Analysts

- CRMs produced by IAEA and other entities
- Radioanalytical methods are validated by analyzing CRMs.
- For a given method, analysts are certified by performing analyses using CRMs.

Certified Reference Materials Studied

- IAEA-384, Fangataufa sediment, French Polynesia, nuclear weapons testing
- IAEA-365, Irish Sea sediment, Sellafield contamination

<table>
<thead>
<tr>
<th></th>
<th>IAEA-384</th>
<th>IAEA-365</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{238}\text{U} )</td>
<td>(35 – 43)</td>
<td>26 – 28</td>
</tr>
<tr>
<td>(^{235}\text{U} )</td>
<td>(1.00 – 1.96)</td>
<td>(1.25 – 1.44)</td>
</tr>
<tr>
<td>(^{232}\text{Th} )</td>
<td>35.0 – 36.8</td>
<td>28 – 30</td>
</tr>
<tr>
<td>(^{238}\text{Pu} )</td>
<td>38.6 – 39.6</td>
<td>0.42 – 0.48</td>
</tr>
<tr>
<td>(^{239,240}\text{Pu} )</td>
<td>103 – 110</td>
<td>2.89 – 3.30</td>
</tr>
<tr>
<td>(^{241}\text{Pu} )</td>
<td>41 – 69</td>
<td>26 – 32</td>
</tr>
<tr>
<td>(^{241}\text{Am} )</td>
<td>6.7 – 7.4</td>
<td>3.76 – 4.01</td>
</tr>
</tbody>
</table>

95% Confidence, Units in Bq/kg, (information only values)

INPC and WSU Technical Exchange on Soil Analysis

- Selected two Certified Reference Materials for analysis by individual methods
  - IAEA 384
  - IAEA 385
- Compare results to certified results; improve methods and operator skills as needed
- Share experiences and recommendations

INPC Approach for Pu Isotopic Analysis

10g Soil

Dissolution

Separation

Total Pu

\(^{239}\text{Pu} \), \(^{238}\text{Pu} \), \(^{237}\text{Pu} \), \(^{236}\text{Pu} \)

Mass spectrometry

GLP: Good Laboratory Practice. GMP: Good Management Practice.
Session #2; Briefing 2: Sue Clark (cont.)

**WSU Approach for Pu Isotopic Analysis**

- Dissolution
- Separation
- Total Pu

- Liquid Scintillation Counting
- Gamma spectrometry
- Alpha spectrometry
- Mass spectrometry

**Pu Analysis in IAEA-384:**
Example of Ratio of $^{238}\text{Pu}$ to $^{239+240}\text{Pu}$

<table>
<thead>
<tr>
<th>Method</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Certified Value</td>
<td>0.364 +/- 0.003</td>
</tr>
<tr>
<td>INPC Results</td>
<td>0.345 +/- 0.025</td>
</tr>
<tr>
<td>WSU Results</td>
<td>0.371 +/- 0.013</td>
</tr>
</tbody>
</table>

- Results by both labs are statistically the same although the methods are slightly different
- High confidence in trace Pu analyses by both labs
- High confidence in both methods

**If we alter our method, we have to re-validate**

- Dissolution
- Separation
- Total Pu

**Method Validation for IAEA-385 $^{239+240}\text{Pu}$, 95% Confidence**

**Analyst Certification, IAEA-385, $^{239}\text{Pu}$ 95% Confidence**

**Additional Opportunities for Confidence Building and International Engagement**

- Additional bilateral and multilateral engagements and technical exchanges
- International Technical Working Group (ITWG) on Nuclear Forensics
  - International association of nuclear forensics experts working with law enforcement, first responders, and regulatory professionals to combat nuclear smuggling
  - Collaboration on technical solutions to common nuclear security problems, including nuclear forensics analysis
  - Developed the Model Action Plan
Session #2; Briefing 2: Sue Clark (cont.)

Summary and Conclusions

- A credible and technically sound nuclear forensics capability can serve as a deterrent against nuclear smuggling and nuclear terrorism.

- Technical nuclear forensics capabilities can only be as robust as:
  - the technical methods used
  - the skill of the analysts involved in the analysis
  - the uncertainties associated with the analyses

- International technical exchanges can help to build confidence and enduring relationships, which are essential for an effective response to a nuclear event.
Session #2; Briefing 3: “Human Capital Development for Nuclear Forensics”, Nathalie Wall (Washington State University)

**Human Capital Development for Nuclear Forensics Programs**

Nathalie A. Wall  
Associate Professor of Chemistry

**Definition**

Nuclear forensics is the collection, analysis, and evaluation of pre-detonation (intact) and post-detonation (exploded) radiological or nuclear materials, devices, and debris, as well as the immediate effects created by a nuclear detonation.

**Nuclear defense spectrum**

A Whole-of-government approach

- U.S. Department of Defense
- U.S. Federal Bureau of Investigation
- U.S. Department of Energy
- U.S. Department of State
- U.S. Department of Homeland Security
- U.S. Office of the Director of National Intelligence

Processes: Model Action Plan

Developed by the Nuclear Smuggling International Technical Working Group (ITWG)

- Incident Response
  - Securing the Incident Site
  - On-site Analysis
  - Radioactive Evidence
  - Traditional Forensic Evidence
  - Final Survey & Release of Scene
  - Evidence Holding Site
  - Evidence Transportation

- Laboratory Sampling & Distribution
  - Nuclear Analysis Laboratory
  - Forensic Management Team
  - Sampling in Nuclear Forensics Laboratory
Session #2; Briefing 3: Nathalie Wall (cont.)

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Developed by the Nuclear Smuggling International Technical Working Group (ITWG)

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U.S. Universities with graduate programs related to Nuclear Chemistry and Technology
25 schools

U.S. Universities with graduate programs related to Nuclear Chemistry and Technology

Nuclear forensics expertise needed
  - at each step of the plan, and
  - for each agency
Session #2; Briefing 3: Nathalie Wall (cont.)

Example of Nuclear Forensics Undergraduate Summer School Funded by the U.S. Department of Homeland Security

- 10 U.S. citizens Undergraduates specializing in Physical Sciences
- Selected by a committee from a large pool of applicants
- Each student receive financial compensation
- Summer school takes place in a university with expertise
- Students have examinations and receive grades
- Each student receive “graduate level” credits to transfer to their own university

Example of Undergraduate Nuclear Forensics Summer School Funded by the U.S. Department of Homeland Security

- 6 weeks:
  - 2 weeks of intensive lecture-based course to learn basics of nuclear and radiochemistry
  - 4 weeks of seminars from specialists from national laboratories and U.S. agencies
  - Hands-on laboratory experiments
  - Field trip to a national laboratory (PNNL), forensics exercise, historic site (B-reactor)

Outcome of the nuclear forensics summer school

- Undergraduates develop an interest in a new field
- Strong bonds with faculty and speakers
- Undergraduates apply to graduate school to pursue a PhD in nuclear forensics or other aspect of nuclear sciences

Conclusion

- Nuclear Forensics process engages multiple U.S. Agencies
- Each step of the nuclear forensics Model Action Plan requires expertise in nuclear forensics
- Human capital development for nuclear forensics programs takes place at all level of the academic career:
  - Undergraduate, graduate, post-doctoral, junior faculty, etc
- Scholarships, fellowships, and other funding are available for all levels
- Nuclear forensics summer school is an efficient way to build expertise with undergraduates
Session #2; Briefing 4: “Numerical Simulation Work on Nuclear Spent Fuel in Nuclear Forensics”, SU Jiahang (Center for Strategic Studies, China Academy of Engineering Physics)

**Outline**
- Introduction
- Numerical simulation works on nuclear spent fuel
  - Characterization of 5MWe Air-cooling Reactor with various isotopic ratios
  - Identification of unknown nuclear spent fuel with multivariate statistics methods

**Introduction**
- The studies on Nuclear Forensics in CSS can be dated back to 10 years ago
- CSS have been looking for proper subjects on Nuclear Forensics, and based on our capability, we have done different numerical simulation work on different aspects, such as
  - Characterization of nuclear spent fuel with isotopic ratios
  - Study of fission products in nuclear explosion
  - Risk analysis for post-detonation scenarios
  - ...

**Numerical simulation work on nuclear spent fuel**
- The attribution of intercepted illicit nuclear or radioactive material is a key component of nuclear forensics
- There are many kinds of materials that should be concerned, an important part of which is nuclear spent fuel
- In our studies, we try to use the isotopic fingerprints to tell the information of unknown nuclear spent fuel, such as
  - Reactor type
  - Initial fuel enrichment and composition
  - Burn-up range (Neutron flux)
  - Cooling time
  - ...

**Background**
- Nuclear irradiation and reprocessing can affect the composition of spent fuel
- So with the study of the composition change of particular isotopes with different burn-up range, reactor type and cooling time, we may tell the feasibility to do the attribution work with such kinds of isotopes in nuclear forensics
- The model we build is a 5 MWe Air Cooling Reactor, with graphite as the moderator
Session #2; Briefing 4: SU Jiahang (cont.)

The study of cooling time

The study of reactor type

The study of burn-up range

Conclusion

- With the methods discussed above, we may have the chance to tell whether the unknown spent fuel is from SMWe Air-cooling Reactor
- Simulations with this method can also be done for different types of reactor with different burn-up range and different cooling time, and then we can characterize them and highlight the difference
- But there are still difficulties to be settled
  ✓ Which isotopes are suitable
  ✓ How much will the difference be
  ✓ Will it be possible for the difference to be measured

Background

- Previous study mainly focuses on looking for proper isotopes to characterize nuclear spent fuel, and the most difficult problem is whether the difference can be measured
- So recently we decide to make some changes by using multivariate statistics to analyze the isotopic fingerprints and try to tell the information such as reactor type, initial fuel enrichment and composition, burn-up range, cooling time, and so on
- Firstly we decide to use factor analysis to compare the spent fuel composition of different reactors, and show the difference
- The main advantage of this method in that we don’t have to find just one or two characteristic isotopes, instead we can combine various isotopes together to enlarge the difference among reactors
Session #2; Briefing 4: SU Jiahang (cont.)

**Methodology**

*Isotopic fingerprints + multivariate statistics*

- U-234
- U-235
- U-236
- Pu-238
- Pu-239
- Pu-240
- Pu-241
- Pu-242

0-Dimensional Simulation

Factor analysis

Dimensionality Reduction

\[ A = A_I + A_{II} + A_{III} \]

- A/B/C/D represents samples that we consider, which are all 8D vectors

**Brief introduction of factor analysis**

- Factor analysis can help simplify the data by extracting the intrinsic characteristics and replacing the previous data with these new parameters
- The larger the correlation of the data is, the fewer will the parameters be after simplifying
- Generally, a 3D plot will be preferred after simplifying if the cumulative contribution is enough for example, above 80%

**Dimensionality Reduction**

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>U-234</td>
<td>A_1</td>
<td>B_1</td>
<td>C_1</td>
<td>D_1</td>
</tr>
<tr>
<td>U-235</td>
<td>A_2</td>
<td>B_2</td>
<td>C_2</td>
<td>D_2</td>
</tr>
<tr>
<td>U-236</td>
<td>A_3</td>
<td>B_3</td>
<td>C_3</td>
<td>D_3</td>
</tr>
<tr>
<td>Pu-238</td>
<td>A_4</td>
<td>B_4</td>
<td>C_4</td>
<td>D_4</td>
</tr>
<tr>
<td>Pu-239</td>
<td>A_5</td>
<td>B_5</td>
<td>C_5</td>
<td>D_5</td>
</tr>
<tr>
<td>Pu-240</td>
<td>A_6</td>
<td>B_6</td>
<td>C_6</td>
<td>D_6</td>
</tr>
<tr>
<td>Pu-241</td>
<td>A_7</td>
<td>B_7</td>
<td>C_7</td>
<td>D_7</td>
</tr>
<tr>
<td>Pu-242</td>
<td>A_8</td>
<td>B_8</td>
<td>C_8</td>
<td>D_8</td>
</tr>
</tbody>
</table>

Here I/II/III are all 8D vectors, but A/B/C/D are reduced to 3D

**Initial values for simulation**

<table>
<thead>
<tr>
<th>Reactor type</th>
<th>Initial</th>
<th>Burn-up range (GWd/MTU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PWR</td>
<td>UO(_2) 3.2%U-235</td>
<td>25-50</td>
</tr>
<tr>
<td>PWR</td>
<td>UO(_2) 3.2%U-235</td>
<td>25-50</td>
</tr>
<tr>
<td>PWR</td>
<td>MOX (Natural U, 4%Pu)</td>
<td>35-60</td>
</tr>
<tr>
<td>BWR</td>
<td>UO(_2)_3.1%U-235</td>
<td>15-25</td>
</tr>
<tr>
<td>CANDU</td>
<td>Natural U</td>
<td>0.3-8</td>
</tr>
<tr>
<td>CANDU</td>
<td>UO(_2) 1.2%U-235</td>
<td>5-20</td>
</tr>
<tr>
<td>LMFBR</td>
<td>MOX (80% U depleted, 12% Plutonium Pu)</td>
<td>50-100</td>
</tr>
</tbody>
</table>

**3D plot for the reactor analysis**

**3D plot of the reactor analysis (with rotation)**
Session #2; Briefing 4: SU Jiahang (cont.)

**Preliminary study on attribution**

- To step further, some known spent fuels are assumed to be unknown.

<table>
<thead>
<tr>
<th>'Unknown' fuel</th>
<th>Reactor type</th>
<th>Fuel</th>
<th>Burn-up range (GWD/TU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unknown1</td>
<td>PWR</td>
<td>UO₂</td>
<td>35U-235</td>
</tr>
<tr>
<td>Unknown2</td>
<td>PWR</td>
<td>UO₂</td>
<td>3.55U-235</td>
</tr>
<tr>
<td>Unknown3</td>
<td>PWR</td>
<td>MOX</td>
<td>Natural U, 48.4%</td>
</tr>
<tr>
<td>unknown4</td>
<td>PWR</td>
<td>MOX</td>
<td>Natural U, 4.55%</td>
</tr>
</tbody>
</table>

**3D plot for the new reactor analysis**

**Details for PWR MOX**

**Conclusion & Future Plan**

- A preliminary study was presented here to compare the spent fuel composition of different reactors, and some ‘unknown’ spent fuels are added to demonstrate the method presented and verify its attribution capability.
- The results show that the method can tell the difference among reactors, so it might be available to use such methods for the attribution.
- Next we will demonstrate the feasibility to use such kinds of methods to do the attribution for nuclear spent fuel in detail.

**Thanks for your attention!**
Session #2; Briefing 5: “Development of Nuclear Forensics Capabilities – A Systems Framing Study”, Larry Brandt (Stanford University)

**Development of Nuclear Forensics Capabilities**  
*An Initial Systems Framing Study*

Larry Brandt  
Center for International Security and Cooperation  
Stanford University

Presented at the Workshop on China – U.S. Technical Cooperation to Reduce the Risks of Radiological and Nuclear Terrorism  
Stanford Center at Peking University  
June 6-7, 2016

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**Important Attribution Questions**

After the intercept of a quantity of radiological or nuclear material, or an assembled device, authorities will ask the following attribution questions:

- What is the original source of the material/device?
- What is the intended purpose of the material/device?
- Where, when, and how has the material/device been processed?
- What route has it taken?
- Who has been involved in the processing and transport?
- Is there more (or related) material out of regulatory control?

An important reminder: Nuclear forensics is not attribution.

Nuclear forensics  
+ Investigation  
+ Intelligence  
→ Attribution

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**Nuclear Forensics – A Systems Framework**

**Key Motivating Questions**

- What strategies can support further development of China's nuclear forensics capability?
- How can analysts and modelers contribute?

**Other Important Considerations**

- How important is international cooperation? What are some useful Cooperative Projects?
- What are some first steps for analysts and modelers?

This briefing will take a systems analysis approach to questions regarding forensics capability development.

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**Nuclear Forensics: “Looking for Clues”**

Analysis of diverse material signatures using nuclear forensics can narrow the set of attribution hypotheses.

A signature is a measurable attribute that can link a material to its source, individuals, or processes.

_Note: A signature is more than characteristics data!_

**Types of signatures:**

- **Physical**  
  - Sample dimensions, color, mineral phases, grain size, morphology, ...
- **Chemical**  
  - Elemental concentrations, trace materials, process residues, ...
- **Isotopic**  
  - Isotopic abundances, parent-daughter concentrations (age datings), ...

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**The Nuclear Forensics Process**

Forensics is an iterative analysis and interpretation process.

- Case knowledge  
- Knowledge bases  
- Archived material  
- Subject matter expertise  
- Qualitative and quantitative models

High confidence forensics interpretations depend on a wide range of technical capabilities.

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**What is needed for an effective forensics capability?**

Required laboratory capabilities and knowledge base depend on which material (and which cycle) is chosen as a focus.
Session #2; Briefing 5: Larry Brandt (cont.)

Two Categories of Signature Development

- **Comparative Signatures**: Drawn from the analysis of samples from known locations and production processes.
- **Predictive Signatures**: Based on theoretical knowledge and modeling of underlying mechanisms at the level needed to identify material origin and processing history.

The Importance of Databases

- Databases are vital elements for national programs.
- They support signature development research.
- Many sources emphasize the need for international data sharing.
- One barrier is sensitive or proprietary information in the databases.
- Some guidance on development of national databases is published.

High Risk Material Interdictions – A Partial History

<table>
<thead>
<tr>
<th>Year</th>
<th>Location</th>
<th>Type</th>
<th>Amount (in kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990</td>
<td>Augsburg, Germany</td>
<td>LEU</td>
<td>1.1 kg</td>
</tr>
<tr>
<td>1992</td>
<td>Podez, Russia</td>
<td>HEU</td>
<td>1.5 kg</td>
</tr>
<tr>
<td>1993</td>
<td>Voronezh, Russia</td>
<td>HEU</td>
<td>0.6 kg</td>
</tr>
<tr>
<td>1994</td>
<td>Tanger, Germany</td>
<td>Pu</td>
<td>0.6 kg</td>
</tr>
<tr>
<td>1994</td>
<td>Landshut, Germany</td>
<td>HEU</td>
<td>0.6 kg</td>
</tr>
<tr>
<td>1994</td>
<td>Munich, Germany</td>
<td>Pu</td>
<td>0.6 kg</td>
</tr>
<tr>
<td>1995</td>
<td>Prague, Czech Republic</td>
<td>HEU</td>
<td>0.41 kg</td>
</tr>
<tr>
<td>1995</td>
<td>Prague, Czech Republic</td>
<td>HEU</td>
<td>0.6 kg</td>
</tr>
<tr>
<td>1995</td>
<td>Moscow, Russia</td>
<td>HEU</td>
<td>1.7 kg</td>
</tr>
<tr>
<td>1995</td>
<td>Ruse, Bulgaria</td>
<td>HEU</td>
<td>4 kg</td>
</tr>
<tr>
<td>2001</td>
<td>Paris, France</td>
<td>HEU</td>
<td>0.6 kg</td>
</tr>
<tr>
<td>2003</td>
<td>Georgia/Azerbaijan</td>
<td>LEU</td>
<td>0.6 kg</td>
</tr>
<tr>
<td>2003</td>
<td>Roteren, Netherlands</td>
<td>HEU</td>
<td>0.9 kg</td>
</tr>
<tr>
<td>2006</td>
<td>Thessaloniki, Greece</td>
<td>HEU</td>
<td>0.6 kg</td>
</tr>
<tr>
<td>2007</td>
<td>Poland-Latvia Border</td>
<td>LEU</td>
<td>0.6 kg</td>
</tr>
<tr>
<td>2010</td>
<td>Thessaloniki, Greece</td>
<td>HEU</td>
<td>18 kg</td>
</tr>
</tbody>
</table>

Past Material Intercepts

- Only a small fraction of intercepts involves high risk materials.
- Observed trafficking of HEU/Pu is not increasing.

Intercepts of High Risk Material

- Only a fraction of the HEU/Pu intercepts are documented – and by only a few laboratories.
- Only a few laboratories.
- Multilateral exercises support development of measurement techniques for high risk materials.
- Routine international sharing of high risk materials data is unlikely.

Nations should work together to prepare for the urgent forensics demands that nuclear crises will place upon them.
Review of Ideas for Modelers and Analysts

- Create a strategy for signature development
  - Develop and prioritize attribution scenarios that drive signature and timeline requirements
  - Assess the relative importance of observed and predicted signatures
  - Analyze approaches to acquire required signature data
  - Assess ability of existing models to support predictive signatures

- Analyze national database needs and options
  - Review international database approaches and suggest China’s approach
  - Prototype database search and statistical analysis tools
  - Work with national stakeholders to develop shared approaches

- Develop technical ideas for “day-to-day” and crisis data sharing
  - “Super database” structures (Luetzenkirchen, 2007)
  - Information barrier concepts for databases (Ref: Jason Reinhardt)
  - Methods drawn from other international sharing arrangements

- Collaborate on plans for international cooperation following crises
  - Preparations might include international exercises or technical table tops

- Consider a first international effort in radiological source forensics
  - Information on sources and events (e.g., post-dispersal) may be more sharable

References


Session #3

Countermeasures to Radiological (“Dirty Bomb”) Threats

Briefing 1: “Review of Nanjing Source Recovery Incident”, ZHANG Zhigang (Nuclear Radiation Safety Center)

A diverted Iridium-192 source was successfully recovered by Chinese authorities in 2014. This event demonstrated the capabilities of China’s radiological and nuclear emergency response capabilities. (An English version of this briefing was not available for inclusion in this workshop summary.)

Briefing 2: “Radiological Terrorism Risk-Based Systems Studies”, Leonard Connell (Pacific Northwest National Laboratory)

This briefing summarized a broad range of technical information regarding the risk analysis of radiological sources and their use in radiological dispersal devices (RDDs). The foundations of risk analysis as applied to radiological attacks are reviewed. The characteristics of radiological sources and attributes that make some more dangerous than others are then outlined. Results from the 2008 National Academies study that highlighted the unique risks of cesium chloride (CsCl) sources are then summarized. Subsequent studies to further understand radiological source risks and the more specific physical and economic consequences of a radiological dispersal attack are referenced. Significant programs have been instituted in the U.S. to reduce the vulnerability of deployed CsCl irradiators.
Session #3; Briefing 2: “Radiological Terrorism Risk-Based Systems Studies”, Leonard Connell (Pacific Northwest National Laboratory)

Radiological Terrorism Risk-Based Systems Studies
June 7, 2016
LEONARD CONNELL, PH.D.
Technical Advisor
Pacific Northwest National Laboratory

Outline
- RDDs and Risk in Context
- Rad Material Risk
- 2008 US National Academy of Sciences Study
- Since the NAS Study
- Summary

The Explosive RDD and “Area Denial”
Lofted material can create wide-area contamination.

Risk = Probability x Consequence
Mathematical risk can be amplified by public perception.
- Public’s perception of risk involves many factors:
  - Understanding of the risk
  - Trust in government information
  - Short-term vs. long-term risk
  - Personal control of risk
  - Benefit/cost of risk
  - Seen vs. hidden risk
  - Equitable sharing of risk

What does this tell us about the public’s perception of Rad Terrorism risk?

Rad vs Nuclear Terrorism Risk (Notional)
Rad Terrorism: lower consequences but higher probability.

RDD Risk Elements
For a complete understanding of RDD Risk, study each box.

Risk-Based RDD Systems Analysis: Look for the “easy” scenarios that lead to high consequences
Session #3; Briefing 2: Leonard Connell (cont.)

Radioactive Decay and Units
International unit (Bq) is very small for RDD analysis.
- 1 Bq = 1 disintegration/sec
- Traditional Unit: Cm (Ci) where 1 Ci = 37 GBq
- 1 TBq = 27 Ci (approximately)

IAEA Categorization of Rad Materials
The IAEA categorization system is based on safety concerns, not RDD Area Denial Consequences.

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>IAEA Category 1 (Extremely Dangerous) (Ci)</th>
<th>IAEA Category 2 (Very Dangerous) (Ci)</th>
<th>IAEA Category 3 (Dangerous) (Ci)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Co-60</td>
<td>810</td>
<td>8.1</td>
<td>0.81</td>
</tr>
<tr>
<td>Cs-137</td>
<td>2,700</td>
<td>27</td>
<td>2.7</td>
</tr>
<tr>
<td>Sr-90</td>
<td>2,200</td>
<td>22</td>
<td>2.2</td>
</tr>
<tr>
<td>Am-241</td>
<td>1,600</td>
<td>16</td>
<td>1.6</td>
</tr>
</tbody>
</table>

IAEA Category 1 and 2 Devices
These 4 radionuclides represent 99.5% of all high activity sources.

Category 1, Cs-60 Teletherapy

Category 1, Cs-137 Self-Contained Irradiator

Category 2, Am-241/Be, Well Logging

Category 2, Ir-192, Radiography

Radionuclide Properties
Properties to consider when assessing material risk.

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Half-life</th>
<th>Specific Activity (Ci/gram)</th>
<th>DownRate (mrad/h @ 1cm)</th>
<th>Chemical Form (typical)</th>
<th>Power to Contaminant (Ci/m^3)</th>
<th>Typical Use and Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Co-60</td>
<td>5.3 yr</td>
<td>100</td>
<td>1.4</td>
<td>Metal</td>
<td>10</td>
<td>Irradiators (~10,000 Ci)</td>
</tr>
<tr>
<td>Cs-137</td>
<td>30 yr</td>
<td>20</td>
<td>0.38</td>
<td>Salt Powder</td>
<td>40</td>
<td>Irradiators (~100 Ci)</td>
</tr>
<tr>
<td>Ir-192</td>
<td>74 d</td>
<td>450</td>
<td>0.6</td>
<td>Metal</td>
<td>100</td>
<td>Radiography (~10 Ci)</td>
</tr>
<tr>
<td>Am-241/Be</td>
<td>432 yr</td>
<td>3.5 (0.005)</td>
<td></td>
<td>Oxide Powder</td>
<td>&lt; 10</td>
<td>Well Logging (~1 Ci)</td>
</tr>
</tbody>
</table>

*These are typical values of specific activity used in actual use. Theoretical values (e.g. 11 Ci/g for Co-60) are for ideally pure materials.
*This is the dose rate per Ci at 1 meter from an idealized 1 Ci source, exposed in a 1 foot stainless steel.
*Radionuclides should not be handled in a clean area. Safety should be observed at 1 meter, the actual contamination levels often exceeding 0.005 Ci/m^3. Hard Metals

Co-60 pellets (teletherapy)

Co-60 stugs (large irradators)

Ir-192 discs
Photos courtesy of Fred Harper and Eric E. Ryder, Sandia Labs
Session #3; Briefing 2: Leonard Connell (cont.)

Experience with Cs-137 Contamination

Cs-137 dispersal accidents result in high economic/social consequences

- Goiania, Brazil Sept. 1987
- Chernobyl, USSR April 1986
- Fukushima, Japan March 2011

Material Vulnerability

Is it too difficult to remove the source?

- Scenario difficulty—a key part of risk-based systems analysis
- Assessments were performed, 2003-2006

2008 NAS Committee Members

A diverse set of subject matter experts.

- THEODORE L. PHILLIPS (chairman), University of California, San Francisco
- EVERETT BLOOM, University of Tennessee—Knoxville
- DAVID R. CLARKE, University of California, Santa Barbara
- LEONARDO W. CONNELL, Sandia National Laboratories
- ROBIN GARDNER, North Carolina State University, Raleigh
- C. RICHARD LIU, University of Houston
- RUTH McNABNE, Conference of Radiation Control Program Directors
- ERVIN B. PODGORS, McGill University
- TOR RAUBENHEIMER, Stanford Linear Accelerator Center
- STEPHEN WAGNER, American Red Cross
- DAVID L. WEIMER, University of Wisconsin at Madison

NAS Committee Recommendation

Phase out the use of high activity cesium-chloride sources.

- Recommendation: In view of the overall liabilities of radioactive cesium chloride, the U.S. Government should implement options for eliminating Category 1 and 2 cesium chloride sources from use in the United States and, to the extent possible, elsewhere.

- The committee suggests these steps
  1. Discontinue licensing of new cesium chloride irradiator sources
  2. Put in place incentives for decommissioning existing sources
  3. Prohibit the export of cesium chloride sources to other countries, except for purposes of disposal in an appropriately licensed facility.

Since the NAS Study: Efforts to Understand and Control CsCl Risk
Session #3; Briefing 2: Leonard Connell (cont.)

CsCl Irradiator Special Security Program

Make it more difficult to steal CsCl sources.

- Design and prototype special kits to be retrofitted to existing CsCl machines. Purpose—delay source removal.
- Validate the delay kits against a baseline Adversary Capability Level (ACL).
- Satisfy constraints set by DHS, DOE, NRC, and manufacturers.
- Pilot for the GTRI In-Device Delay program (IDD)

CsCl Alternate Material Risk Study (2009)

As ACL increases, more difficult RDD designs are possible.

RDD Difficulty

- Multi-Step RDDs Optimized
- Multi-Step RDDs Non-Optimized
- 1-Step RDDs

ACL-1 ACL-2 ACL-3
Adversary Capability Level

Adversary Capability Affects RDD Consequences

DHS/EPA relocation guide is set at 2 rem for the 1st year after event.

2 rem, 1st yr
2 rem, 1st yr

A more capable adversary could create a much larger economic impact.

RDD Economic Impacts

Three different cost components:

- Event Recovery Costs – 1-year, usually assessed.
- Business Impact Costs – usually computed over the first year.
  - Direct – Lost GDP from business affected inside denial area.
  - Indirect – Lost GDP from business affected outside denied area.
  - Induced – Lost GDP from reduced spending by affected households.
- Perception Based Costs – can persist, many years.
  - Willingness to purchase goods/services from region.
  - Willingness to invest in region.

RDD Risk Reduction Countermeasures

RDD risk is manageable.

Summary & Conclusions