Overview of U.S. Technical Nuclear Forensics and Material Forensics R&D Activities

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**Nuclear Forensics – What and Why**

- **Technical Nuclear Forensics** (TNF) is the thorough collection, analysis, and evaluation of pre-detonation and post-detonation nuclear and radiological materials, devices, and post-detonation debris, as well as the prompt effects created by a nuclear detonation.

- TNF interprets signatures to identify the type of material, how the material could be used, and how the material was produced.

**Technical Nuclear Forensics**

1. An event/interdiction occurs

2. **Collection:** data and samples

3. **Analysis:** measurements/data are analyzed for signatures

4. **Evaluation:** interpreting signatures; leads to TNF conclusions

**Signature Interpretation Requires Knowledge of:**

- Manufacturing/Production Processes
- Nuclear and Radiological Materials
- Device Designs

**Collection** + **Characterization (measurements + interpretation)**
Nuclear Forensics: an inherently interagency mission, with a foundation built on the National Laboratories

Multiple agencies and labs with specified missions and skills… our goal is to integrate, synchronize and leverage across the USG – unity of effort – enduring capability.

NTNFC: “system integrator” -- centralized planning, evaluation, & stewardship
International Cooperation is Essential

Working with partners to advance international goals and TNF capabilities

“Nuclear forensics and attribution are relatively new concepts. Owing to the complex requirements that call for capabilities from both classical and nuclear forensics, only a small number of States have the resources and capabilities to conduct this combined examination. For this reason it is important to promote international cooperation in nuclear forensics in order to handle it in a systematic manner and to share expertise. To this end, the IAEA has developed in cooperation with the International Technical Working Group on Nuclear Smuggling (ITWG) a common framework to pursue nuclear forensic investigations and best scientific approaches to the collection and interpretation of nuclear forensic evidence.”

Linking with Signature Families

Sample Matching / Exclusion
- Comparison among questioned samples or between questioned and pre-existing reference samples

Inferences about an Unknown Process
- Information about processes can be deduced even if there is no exact match between questioned and pre-existing reference samples
  - Predictive Signatures (Based on Sound Science & Engineering)
  - Material not readily accessible / available

Technical Conclusions
- Linking TNF signature combinations to processes, geo-locations, and/or types of facilities

“Match” Criteria
- Matches / Excludes with Known or Predicted Signature Families
- Involves Combinations of TNF Signatures
- Includes Associated Confidence Level
- Identical to within Analytical Precision
**Signature Combinations: Keys to Discriminating Among Materials**

<table>
<thead>
<tr>
<th>HUMAN FORENSICS</th>
<th>FORENSIC SIGNATURE</th>
<th>NUCLEAR FORENSICS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male / Female</td>
<td>GENDER</td>
<td>Uranium / Plutonium</td>
</tr>
<tr>
<td>Age</td>
<td>AGE</td>
<td>Age-Dating</td>
</tr>
<tr>
<td>Height / Weight</td>
<td>PHYSICAL PROPERTIES</td>
<td>Microstructure / Morphology</td>
</tr>
<tr>
<td>A, B, or AB</td>
<td>BLOOD TYPE</td>
<td>Major Isotopics:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>U: U-235, U-238, U-236, U-234, U-233</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pu: Pu-239, Pu-240, Pu-241, Pu-242</td>
</tr>
</tbody>
</table>

For a population of 1000 persons, using HUMAN FORENSICS signatures:

- ONE forensic signature will not identify a suspect
- All FOUR forensics signatures together will not identify a suspect will high confidence, but will
  - Exclude groups of persons from further consideration
  - Fine tune investigative priorities and next steps
- Additional signatures are needed to effectively discriminate
- Same situation is true for NUCLEAR FORENSICS
Signatures are created, persist, and modified throughout the fuel cycle

Aim to determine the mechanisms that control signature development
NTNF Expertise Pipeline Challenges

Health and prospects for an enduring workforce & capability

Academia

Interns, Post-Docs
Age < 40

Juniors
Age 40 - 50

Mid-Career

Seniors
Age 50+

Other Lab / DOE Programs

Other Programs / Careers

Other Programs

Retirement
Steps to Improve the Workforce Pipeline

• Developed and are implementing the National Nuclear Forensics Expertise Development Program (NNFEDP) with DOE and DoD: a comprehensive interagency program that is enduring and provides a stable foundation from which to restore and maintain the technical nuclear forensics workforce
  — Secondary and undergraduate outreach
  — Undergraduate and graduate internship programs
  — Graduate fellowship program
  — Post-doctorate programs at National Labs and universities
  — University education awards
  — Funding of academic research efforts
Key Messages

- Nuclear Forensics is an emerging discipline – requirements and questions today are different from in the past -- building upon foundational capabilities and requiring new

- It is one of the components supporting attribution; Not equivalent to DNA or fingerprint forensics, rather a multi-layered, deductive process

- Exclusion can be crucial; Exculpatory arguments are powerful

- International collaboration is essential -- various activities gaining momentum

- Must assure readiness through exercises

- Expertise must be recruited & retained to ensure credible future forensics capability
MATERIALS FORENSICS R&D ACTIVITIES
Pre-Det Materials Forensics: The Process

1. **Collection**
   - Interdiction or Garnering Materials

2. **Analyses**
   - Analyses of Materials
     - **Nuclear Forensics**
       - Isotopic Composition
       - Chemical Composition
       - Physical Structure
       - Pathways Analyses
     - **Traditional Forensics**
       - Latent Fingerprints
       - Genetic Markers
       - Explosives
       - Fibers, Residues, etc.

3. **Evaluation**
   - Evaluation Tools and Expert Interpretation
   - Technical Nuclear Forensics Conclusions
Materials Signatures Development Program

- **Vision:** A validated set of chemical, isotopic, and physical signatures that distinguishes the origin and history of nuclear and radiological materials.

- **Objectives:**
  - Cover materials across the globe
  - Cover the entire nuclear fuel cycle of the materials
  - Delineate the mechanisms and phenomena that control signatures creation, persistence, and modification
  - Use the most informative possible set of signatures
  - Adhere to the basic forensic investigation principles:
    - Traceable reference standards
    - Validated methods
    - Demonstrated competencies
Particle Morphology Comparison: Yellow Cake Powders

Morphological differences apparent:
- orange: finely divided spherical particles
- yellow: finely divided globular particles
Trace impurities can reveal information about fuel fabrication

- In general, fuel pellets have few impurities—even at the ppm level, but some evidence of process can be seen.
- For example, Mfr. 2 used Aluminum Stearate as a mold release agent; Mfrs. 1 and 3 did not; mass spectrometer detects Al at 30-60 ppm consistently in pellets from Mfr. 2.
- The presence of trace contamination in pure UO₂ pellets also appears to be a promising signature.

Fuel pellets analyzed from 3 US commercial manufacturers (Global Nuclear Fuels, Areva, Framatome)
Multiple forensics signatures provide clues

A broad range of analyses were used to examine Bulgarian HEU seizure

**Non-nuclear forensics**

- Wax material fingerprint
- Wax colorant
- Paper origin
- Pb metallurgy
- Pb isotopics
- Ampoule material

**Nuclear material forensics**

- Morphology
- Chemical Composition
- Trace elements
- Residual radionuclides
- Age-dating
- U & Pu isotopics
Nuclear Forensics Knowledge Management & Assessment System (KMAS) Enables Rapid and Credible Interpretation of Signatures

**SIGNATURE ANALYSES**
- Isotopics
- Chemical Comp.
- Trace Elements
- Microstructure
- Morphology
- Age Dating
- Pathways Analyses

**EVALUATION PROCESS**

**TECHNICAL CONCLUSIONS**
- Reveals patterns in TNF data
- Resolves unanticipated and novel findings
- Enables signature discovery
- Links TNF signatures to manufacturing processes, geo-locations, types of facilities based on sound science

**MINING & LINKING**
Signature Data

**PATTERN CLASSIFICATION**

**MATERIAL PRODUCTION TIMELINES**

**SIGNATURE MODELING & VALIDATION**

**CAPTURE & LINKING OF EXPERT KNOWLEDGE**
Multi-Variate Analysis Provides Mathematical Techniques for Comparing with Known Signature Families

Multi-Variate Pattern Analysis Enables:

- Formulation of classification schemes for unknowns using existing nuclear forensics databases
- Identification of the most discriminating features distinguishing groups within nuclear forensics data
- Determination of inclusion / exclusion of unknown samples according to classification schemes (e.g. group membership)

3 Step Process:
- Variable Discrimination
- Cluster Analysis
- Pattern Classification
Decision Tree Shows Yellowcake From Mines Can Be Roughly Defined By Trace Element Concentration

Historical example using literature data from 214 worldwide samples from 81 mines

(Literature Data Courtesy of DOE/NA-243)
SFCOMPO - Spent Fuel Isotopic Composition Database

Developed by Fuel Cycle Safety Evaluation Laboratory at the JAERI Department of Fuel Cycle Safety Research. Operated by the NEA Nuclear Science Division under the supervision of the Working Party on Nuclear Criticality Safety.

SFCOMPO, the Spent Fuel Isotopic Composition Database, was originally developed at the JAERI Department of Fuel Cycle Safety Research's Fuel Cycle Safety Evaluation Laboratory. SFCOMPO provides isotopic composition data via the internet [Ref 3 and 4]. It archives measured isotopic composition data and the values of their ratios, which are required for the validation of burn-up codes.

Based on discussions at a meeting of the Working Party on Nuclear Criticality Safety (WPNC) held in December 2001, a system of SFCOMPO for internet dissemination was transferred from JAERI to the NEA Data Bank. The system is now operated by the NEA.
Addressing Group Inclusion/Exclusion Problems using Principal Component Analysis (PCA)

Sample with large $Q$ statistic:
Unusual variation outside model

Sample with large $T^2$ value:
Unusual variation inside model

Sample consistent with model (small $T^2$ and $Q$)
SFCOMPO: Isotopic Ratios Used in Building Global and Group Specific PCA Models

- 5 isotopic ratios available for all 14 reactors used:
  - $^{240}\text{Pu}/^{239}\text{Pu}$, $^{241}\text{Pu}/^{239}\text{Pu}$, $^{242}\text{Pu}/^{239}\text{Pu}$, $^{235}\text{U}/^{238}\text{U}$, $^{236}\text{U}/^{238}\text{U}$
SFCOMPO: Global PCA Model of All 14 Reactors

- Principal Components Analysis (PCA) incorporates information from 5 isotopic ratios in lower dimensional space
### Examples of World-Wide PUREX Reprocessing Plants

<table>
<thead>
<tr>
<th>Country</th>
<th>Plant</th>
<th>Precipitation</th>
<th>Finishing</th>
</tr>
</thead>
<tbody>
<tr>
<td>America</td>
<td>SRS F-Canyon</td>
<td>Pu(III) - HF(aq)</td>
<td>Bomb reduction</td>
</tr>
<tr>
<td></td>
<td>Hanford Z-Plant</td>
<td>Pu(IV) - oxalate</td>
<td>HF(g) / Bomb reduction</td>
</tr>
<tr>
<td></td>
<td>Hanford Purex (N-Cell)</td>
<td>Pu(IV) - oxalate</td>
<td>Air calcination</td>
</tr>
<tr>
<td>England</td>
<td>B205 Magnox</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sellafield- THORP</td>
<td>Pu(IV) - oxalate</td>
<td>Air calcination</td>
</tr>
<tr>
<td>France</td>
<td>La Hague UP2 (D)</td>
<td>Pu(IV) - oxalate</td>
<td>Air calcination</td>
</tr>
<tr>
<td>Japan</td>
<td>Tokai-Mura</td>
<td>Mixed U/Pu solution</td>
<td>Microwave Denitration</td>
</tr>
<tr>
<td></td>
<td>Rokkasho-Mura</td>
<td>Mixed U/Pu solution</td>
<td>Microwave Denitration</td>
</tr>
<tr>
<td>North Korea</td>
<td>Yongbyon Nuclear Scientific Res’h Center</td>
<td>Pu(III)-oxalate</td>
<td>Bomb reduction</td>
</tr>
<tr>
<td>Russia</td>
<td>Mayak/ RT-1</td>
<td>Pu(IV)-oxalate</td>
<td>Air calcination (?)</td>
</tr>
<tr>
<td></td>
<td>Tomsk-7</td>
<td></td>
<td>Bomb reduction</td>
</tr>
<tr>
<td></td>
<td>Krasnoyarsk-26/ RT-2</td>
<td>Mixed U/Pu solution</td>
<td>Plasma denitration</td>
</tr>
</tbody>
</table>
QA Systems in Nuclear Forensics

• Measurements must be scientifically and legally defensible
• QA systems: Provide a high level of confidence and reliability in measurements
• Actionable conclusions in matters of nuclear proliferation, smuggling, and terrorism depend on QA of data and results
• Quality in Conclusions: Achievable through performance testing and assessments of laboratory capabilities and operational status
Principles of Best Analytical Practice

- Independent assessments of technical performance are performed on a regular basis (i.e., Performance Testing using blind reference materials)

- Independent audits of internal laboratory QA practices are performed on a regular basis

- Development of measurement methods link to standard reference materials

- All measurement procedures are validated: Performance capabilities are consistent with application requirements (i.e. fit for purpose)

- Staff performing analytical measurements are qualified and competent

- Traceable Reference Standards

- Validated Methods

- Demonstrated Competencies

✓ Independent assessments of technical performance are performed on a regular basis (i.e., Performance Testing using blind reference materials)

✓ Independent audits of internal laboratory QA practices are performed on a regular basis