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 = ***Collection*** + ***Characterization (measurements + interpretation)***

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

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."

IAEA, 2007, "Reference Manual on Combating Illicit Trafficking in Nuclear and Other Radioactive Material"

IAEA
International Atomic Energy Agency

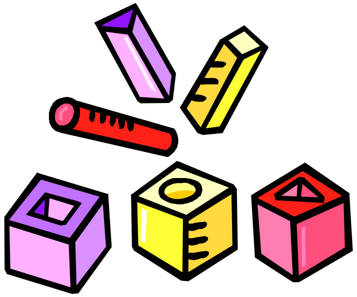
ITWG
Nuclear Forensics

Nuclear Security Summit
Washington, 2010

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

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

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**

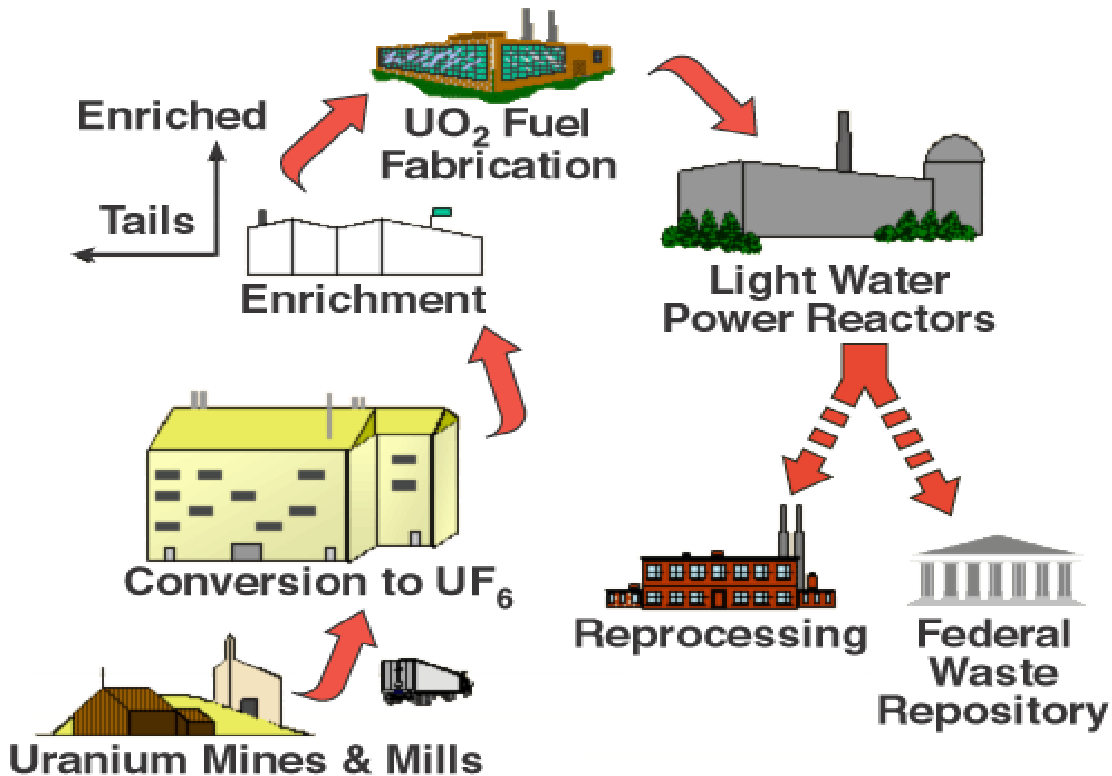
Signatures are created, persist, and modified throughout the fuel cycle

Thorough knowledge of signature evolution throughout the Nuclear Fuel Cycle enables:

✓Linking of materials to production processes, geo-locations, and types of facilities based on science and engineering

✓Targeting of predictive signatures for materials not readily accessible or available

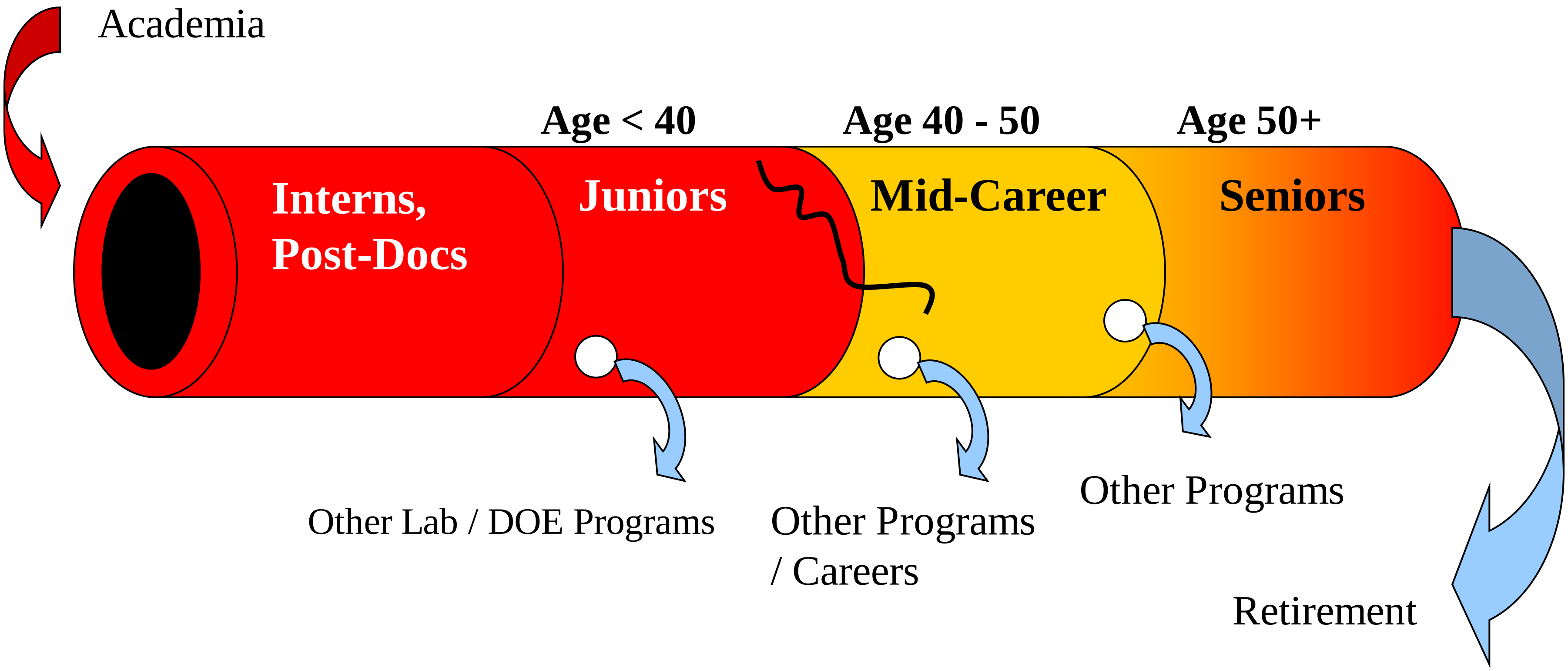
✓Provides a robust background for potential resolution of unanticipated novel findings in TNF



Aim to determine the mechanisms that control signature development

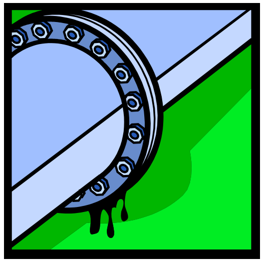
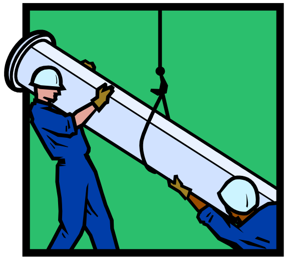
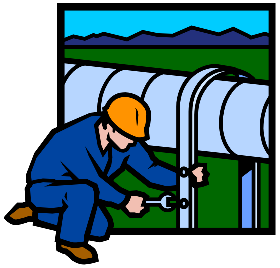
NTNF Expertise Pipeline Challenges

Health and prospects for an enduring workforce & capability



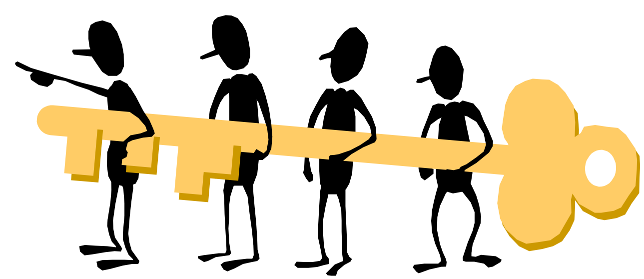
Steps to Improve the Workforce Pipeline

- **Developed and are implementing the National Nuclear Forensics Expertise Development Program (NNFEDP) <u>with DOE and DoD</u>: 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**

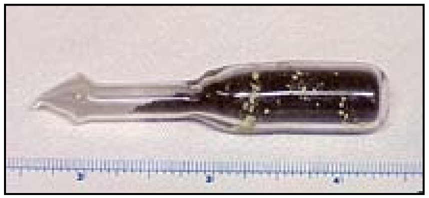


MATERIALS FORENSICS R&D ACTIVITIES

Pre-Det Materials Forensics: The Process

1. Collection

Interdiction or Garnering Materials



2. Analyses

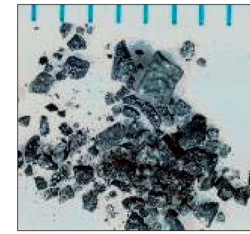
Analyses of Materials

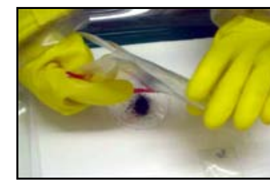
Nuclear Forensics

- Isotopic Composition
- Chemical Composition
- Physical Structure
- Pathways Analyses

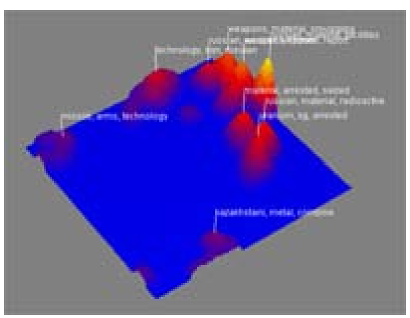
Traditional Forensics

- Latent Fingerprints
- Genetic Markers
- Explosives
- Fibers, Residues, etc.

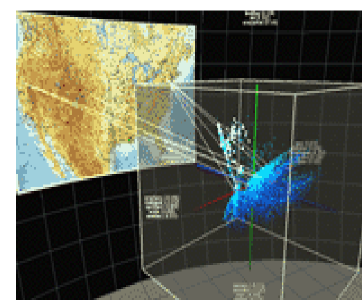




3. Evaluation



Evaluation Tools and Expert Interpretation

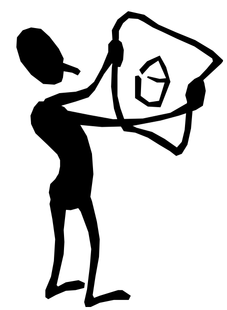


Technical Nuclear Forensics Conclusions

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.***

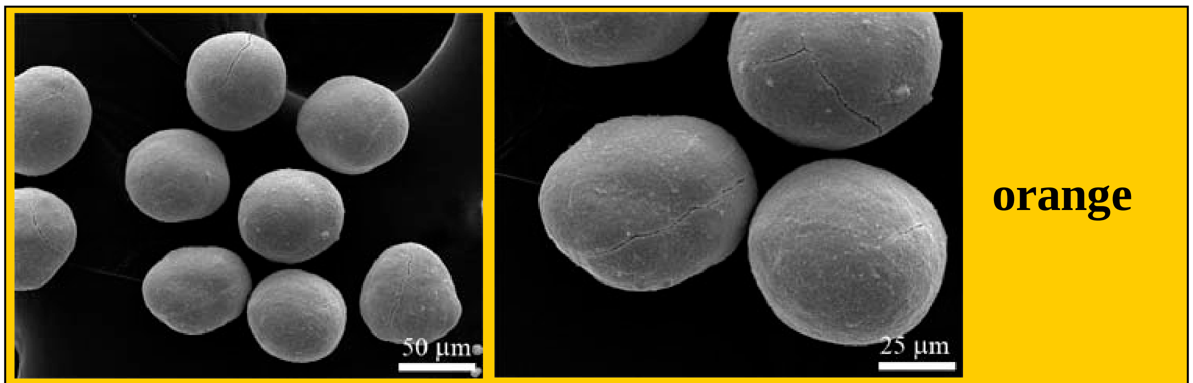
- **Objectives:**
  - — *Cover materials across the globe*
  - — *Cover the entire nuclear fuel cycle of the materials*
  - — *Delineate the mechanisms and phenomena that control signatures creation, persistence, and modification*
  - — *Use the most informative possible set of signatures*
  - — *Adhere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



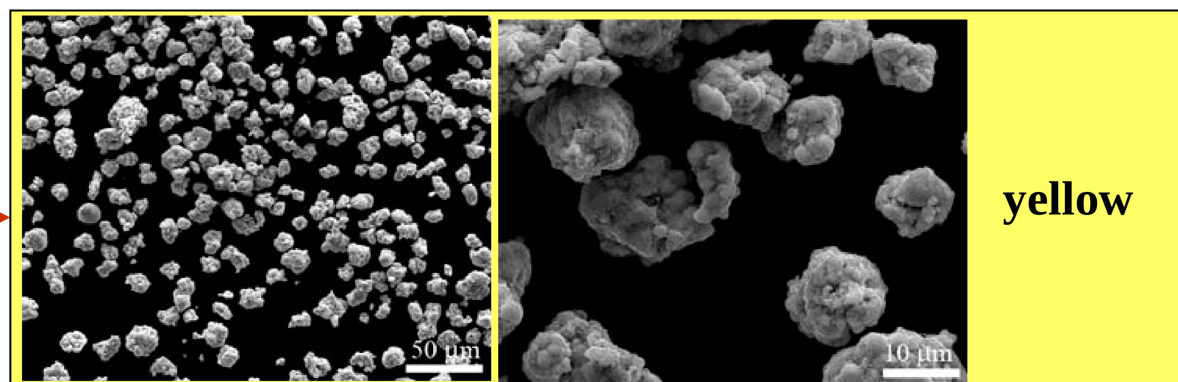
Particle Morphology Comparison: Yellow Cake Powders

Morphological differences apparent:

orange: finely divided spherical particles
yellow: finely divided globular particles

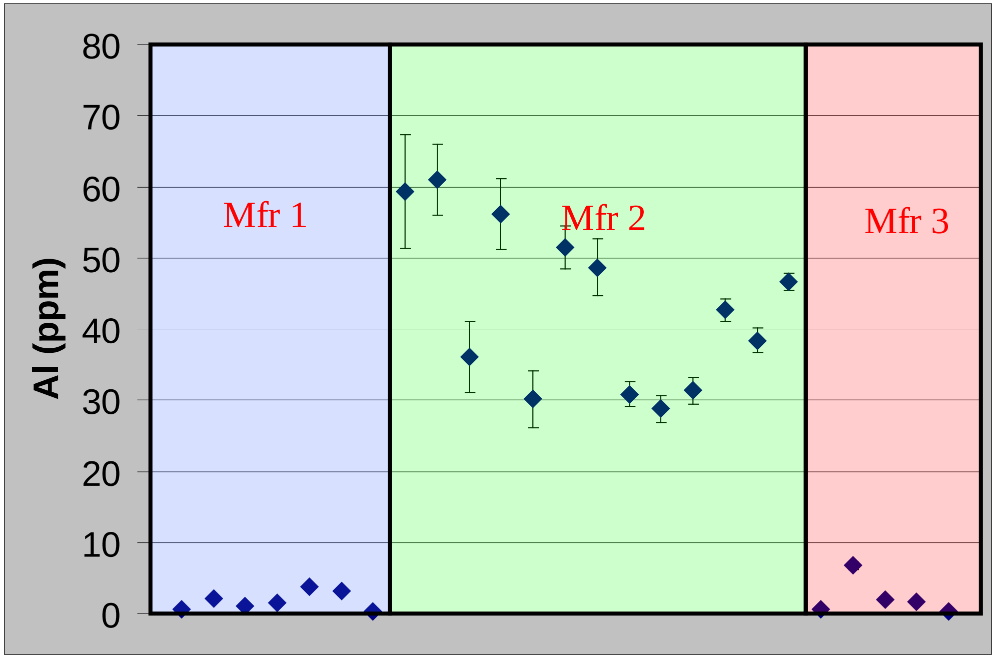


Same Magnification



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 UO_2 pellets also appears to be a promising signature.



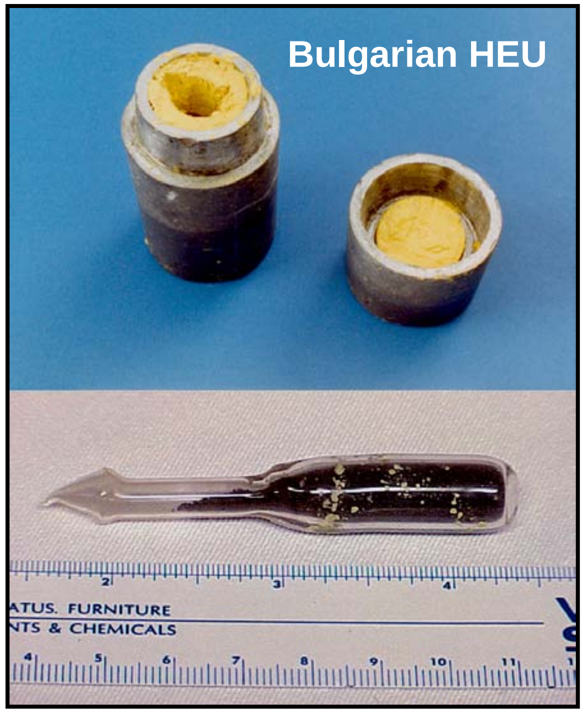
Fuel pellets analyzed from 3 US commercial manufacturers (Global Nuclear Fuels, Areva, Framatome)

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

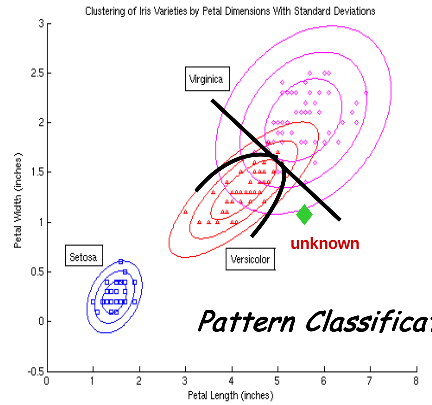
Nuclear Forensics Knowledge Management & Assessment System (KMAS) Enables Rapid and Credible Interpretation of Signatures

SIGNATURE ANALYSES

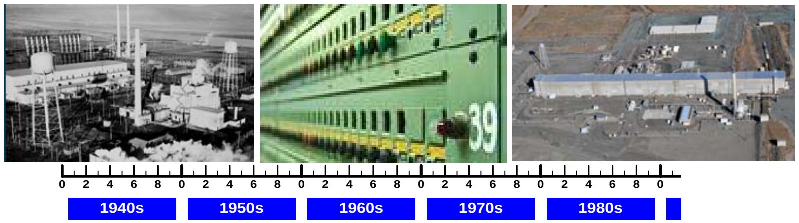
- Isotopics
- Chemical Comp.
- Trace Elements
- Microstructure
- Morphology
- Age Dating
- Pathways Analyses

via KMAS

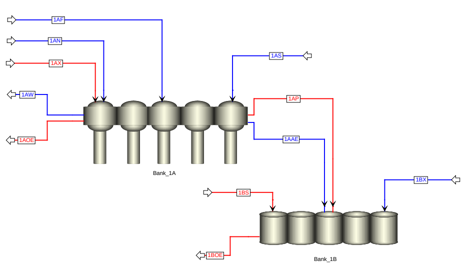
Mining & Linking Signature Data



Pattern Classification



Material Production Timelines



Signature Modeling & Validation

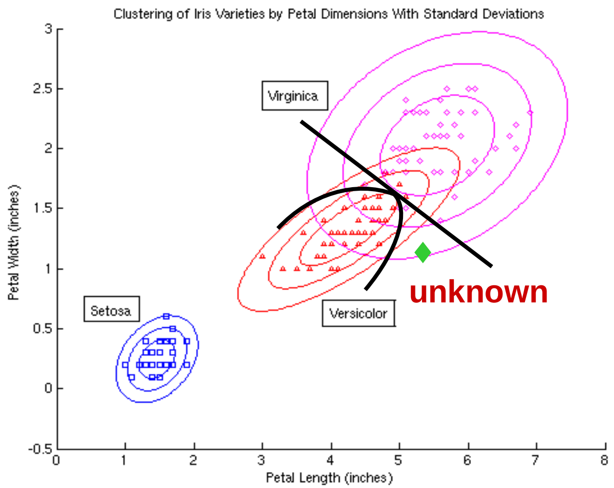
Capture & Linking of Expert Knowledge

EVALUATION PROCESS

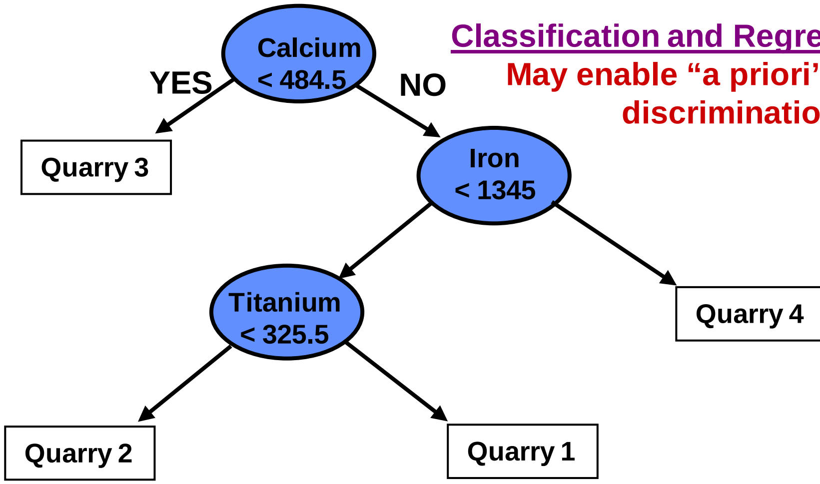
TECHNICAL CONCLUSIONS

- 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

Multi-Variate Analysis Provides Mathematical Techniques for Comparing with Known Signature Families



Cluster analysis: **Determines group membership of an unknown**



Classification and Regression Trees: **May enable “a priori” variable discrimination**

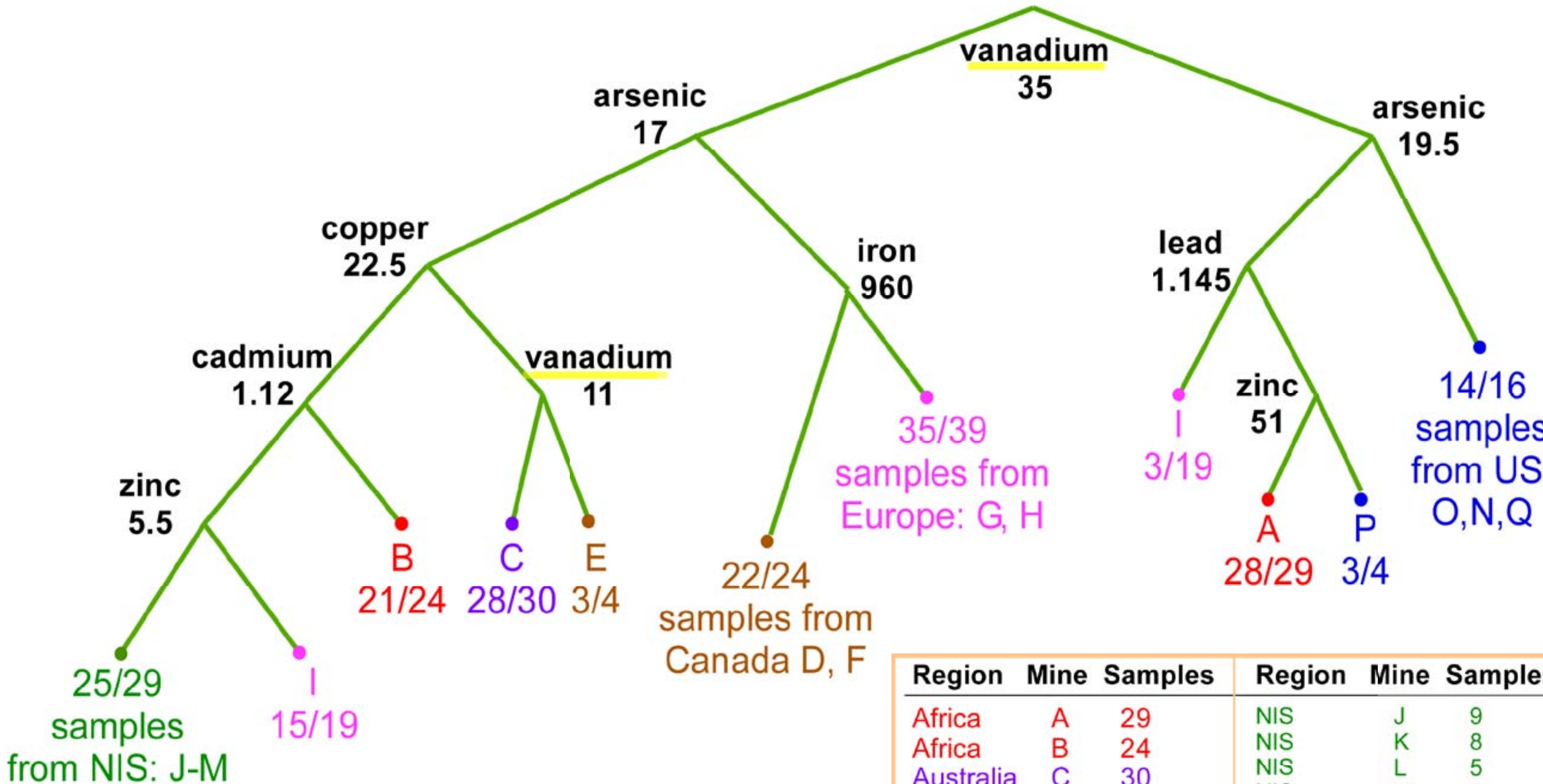
Multi-Variate Pattern Analysis Enables:

- 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

Region	Mine	Samples	Region	Mine	Samples
Africa	A	29	NIS	J	9
Africa	B	24	NIS	K	8
Australia	C	30	NIS	L	5
Canada	D	10	NIS	M	7
Canada	E	4	US	N	5
Canada	F	14	US	O	5
Europe	G	20	US	P	4
Europe	H	19	US	Q	6
Europe	I	19			

(Literature Data Courtesy of DOE/NA-243)

SFCOMPO: Spent Fuel Isotopic Composition Database

AEN NEA Agence pour l'énergie nucléaire
Nuclear Energy Agency

OECD

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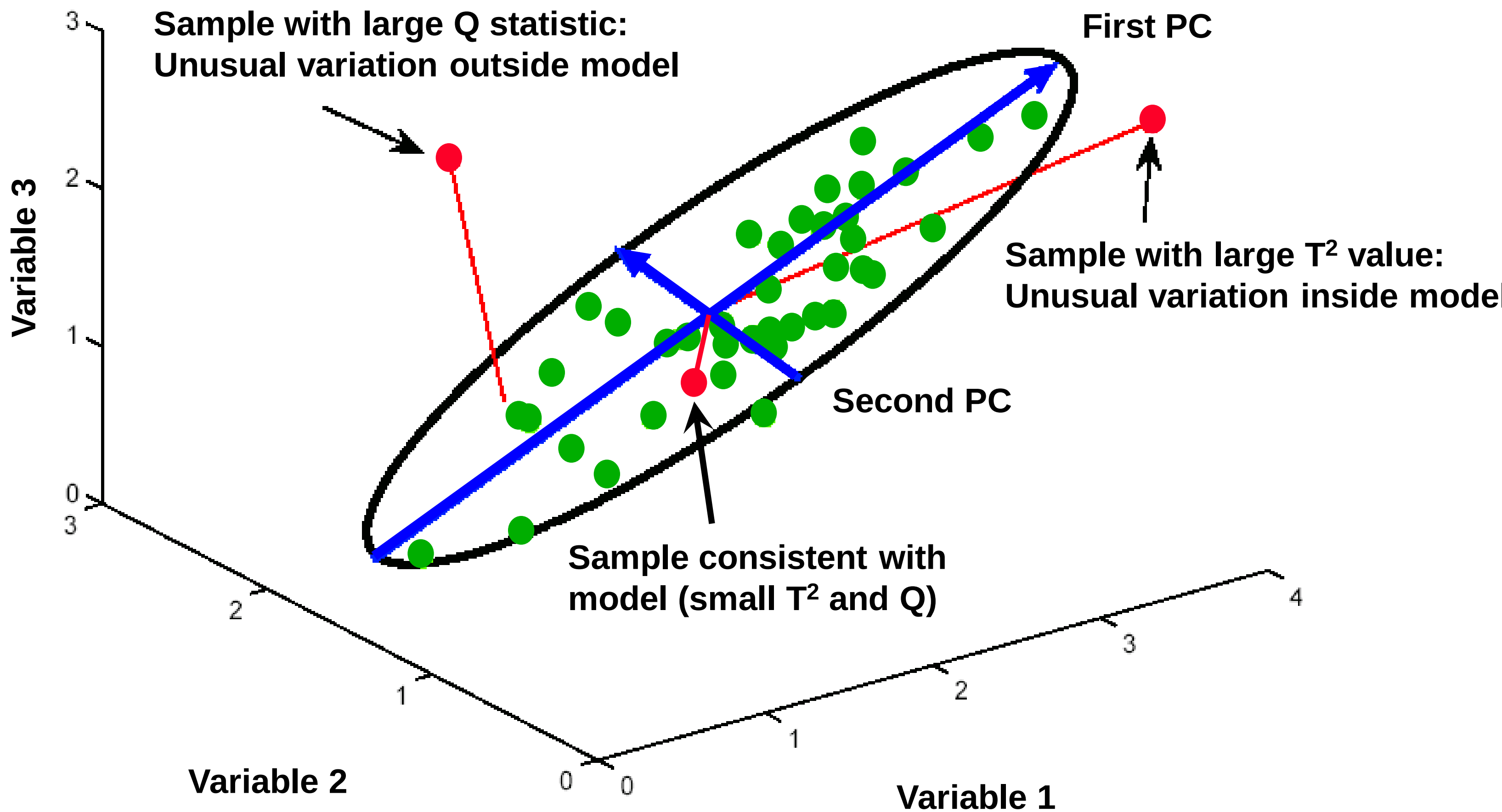
SFCOMPO - Spent Fuel Isotopic Composition Database

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.

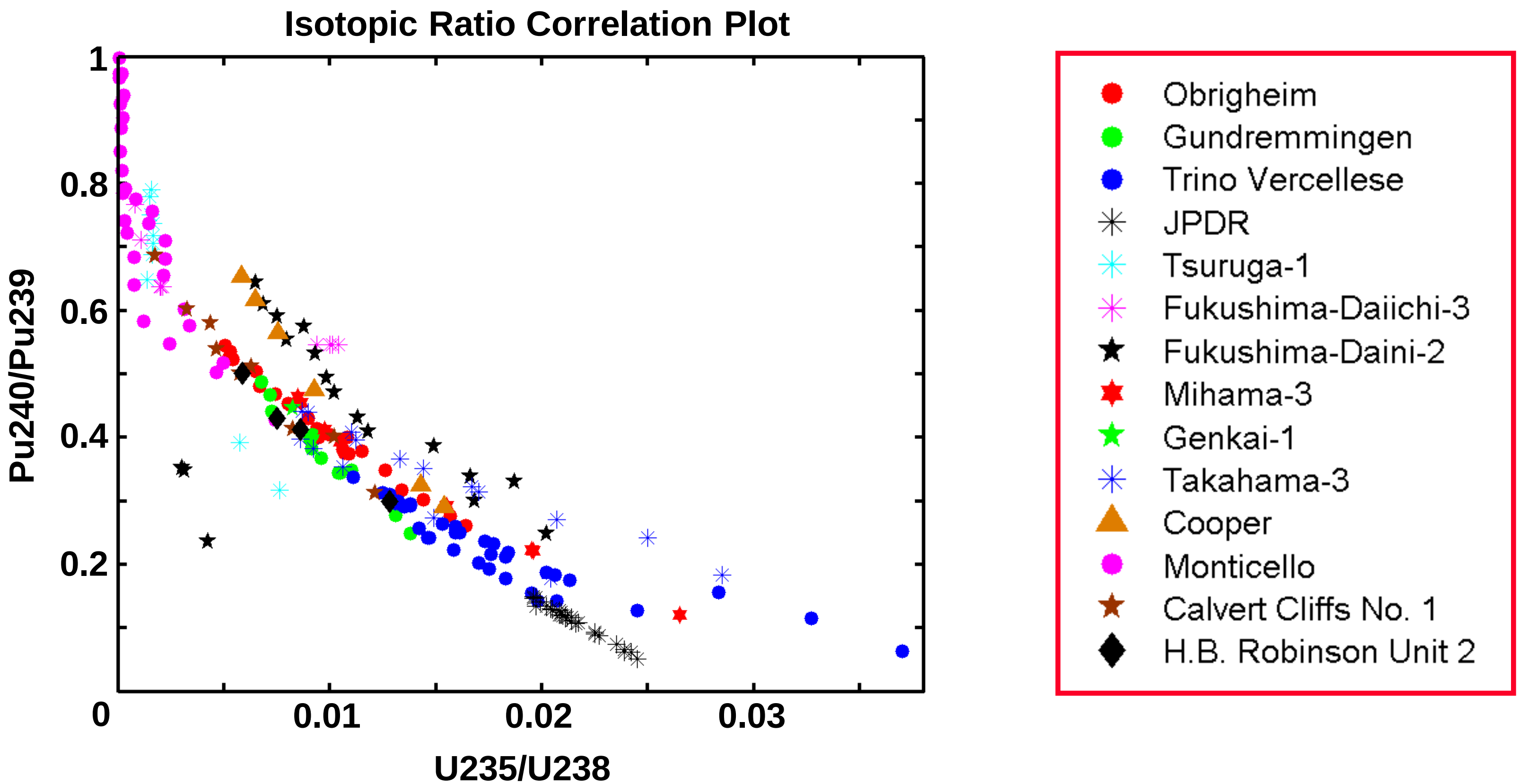
Based on discussions at a meeting of the Working Party on Nuclear Criticality Safety (WPNCS) held in December 2001, a system of SFCOMPO for internet dissemination was transferred from JAERI to the NEA Data Bank. The system is now operated by the NEA.

Addressing Group Inclusion/Exclusion Problems using Principal Component Analysis (PCA)



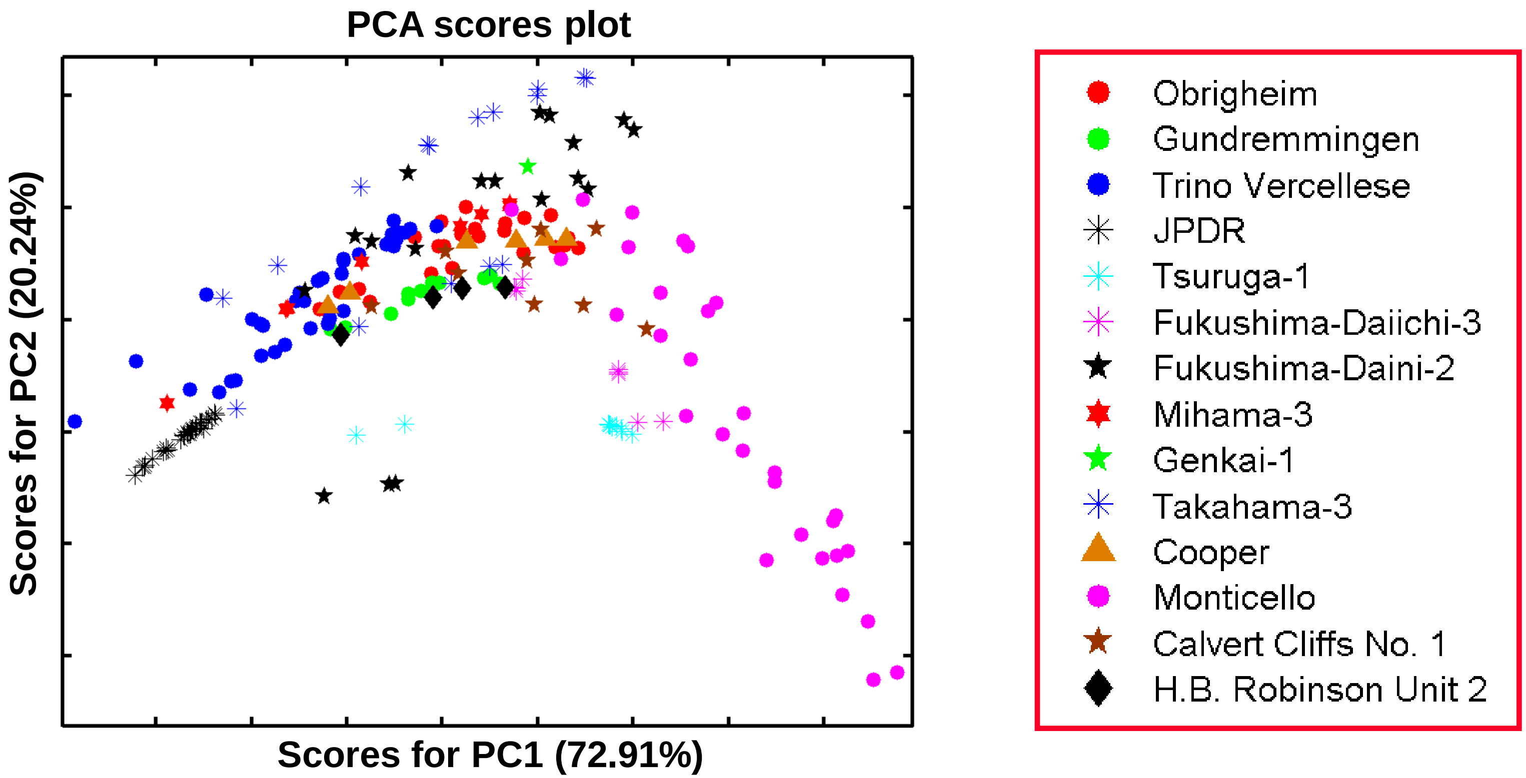
SFCOMPO: Isotopic Ratios Used in Building Global and Group Specific PCA Models

- **5 isotopic ratios available for all 14 reactors used:**
  - $^{240}Pu/^{239}Pu$, $^{241}Pu/^{239}Pu$, $^{242}Pu/^{239}Pu$, $^{235}U/^{238}U$, $^{236}U/^{238}U$



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

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

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

Traceable Reference Standards

Development of measurement methods link to standard reference materials

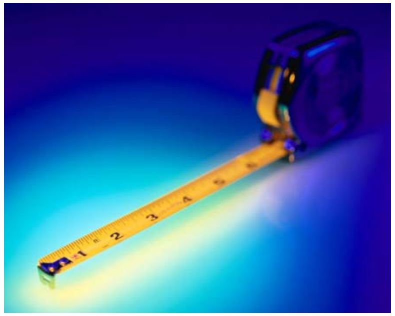
Validated Methods

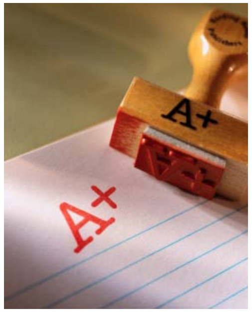
All measurement procedures are validated: Performance capabilities are consistent with application requirements (i.e. fit for purpose)

Demonstrated Competencies

Staff performing analytical measurements are qualified and competent

- ✓ **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**





Homeland Security