Use of Gamma Spectrometry in the UKNI Information Barrier Project

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on behalf of the UKNI Collaboration

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Participants

- Collaboration began in 2007
- Participating institutions
  - UK: Atomic Weapons Establishment (AWE), Ministry of Defence
  - Norway: Institute for Energy Technology (IFE), Norwegian Defence Research Establishment (FFI), NORSAR, Norwegian Radiation Protection Authority (NRPA)
  - NGO: Verification Research Training and Information Centre (VERTIC) participated until 2009
Outline

• Will cover a few key topics:
  – Project background and information barrier concept
  – IB algorithm design & test
  – Major issues to consider & where next

• All project information – design drawings, software, analyses etc. – is available at http://ukni.info
Part 1

BACKGROUND AND CONCEPT
The Information Barrier project

- **Project objective:** Understand how to build and maintain *mutual confidence* in verification equipment.
  - Investigate joint hardware/software design
  - Design for equipment authentication

- *(Fictional) monitoring objective:* Allow inspectors to verify that an object declared to be a Treaty Accountable Item (TAI) has the attributes it should, without revealing any other details:
  - TAI* contain plutonium*; and
  - Plutonium in TAI* has a $^{240}\text{Pu} : ^{239}\text{Pu}$ ratio of <0.1

- **UKNI** pursued these objectives by designing and building an information barrier consisting of a high resolution gamma detector and custom electronics
Information Barrier project steps

• Phase 1: Identification of $^{60}\text{Co}$

• Phase 2: Ratio calculation of $^{60}\text{Co}$ and $^{22}\text{Na}$

• Phase 3: Plutonium identification, $^{240}\text{Pu}/^{239}\text{Pu}$ ratio calculation, comparison vs. preset threshold of 0.1
  – Phase 3a: Area calculation algorithm
    – Performance tested using data collected at Dounreay civil nuclear facility
  – Phase 3b: Peak fitting algorithm
    – Performance tested using data collected at AWE
Authentication concept

**Overall design and implementation**

1. Joint design
2. Host production
3. Authentication process
4. Deployment under dual custody

**Software**

1. Analysis to be performed
2. Agreed mathematical form
3. Convert into programming language
4. Binary code
5. Authentication process
Authentication process

- Initial concept: Give equipment to inspectors after use
- ‘Post-use’ authentication difficult to achieve in practice
- Reliance on random selection and authentication ‘by association’
Part 2

ALGORITHM DESIGN & TEST
Algorithm flow

- Calibration is performed nearly identically in both Phase 3a and Phase 3b algorithms:
  - IB software locates two prominent gamma peaks from a $^{152}$Eu source
  - Only proceeds to measurement if successful

- Measurement
  - Stage 1: Pu identification (300 – 500 keV ROI)
  - Stage 2: Isotopic ratio calculation (630 – 670 keV ROI)

- Calibration verify identical to calibration
  - Parameters might drift over time due to e.g. heating or a change in environmental background
  - Failure at this stage casts doubt on measured result
Plutonium identification

• Choose suitable peaks: 345 keV, 375 keV, 392/3 keV, 413 keV, 451 keV

• How to ensure peaks are from plutonium?

• Originally discussed five tests
  1. Peak location
  2. Peak shape
  3. Peak presence
  4. Relative peak height
  5. Relative peak location

• Only first three deemed suitable
  – No gamma background information so ‘relative peak height’ is not useful
  – Relative peak location unnecessary as absolute location needs to be hard-coded in software
Phase 3a testing

- Plutonium measurements at Dounreay – different types & quantities
  - Varying isotopic content around threshold (0.1 $^{240}\text{Pu}/^{239}\text{Pu}$)
  - Relatively large mass (200 – 900 g)
  - Standard container design (minimal shielding)

- Multiple IBs deployed on signal from single HPGe detector

- Results: Accuracy & precision insufficient, developed improved algorithm → Phase 3b
Part 3

ISSUES TO CONSIDER
Threshold setting

- **False positives**, identification of Pu (with $^{240}\text{Pu}/^{239}\text{Pu} < 0.1$) if such material is not present
- **False negatives**, confirmation not given when material with suitable attributes is present
- Error rate clearly greatest around the threshold value
- The threshold can only be set using results from unclassified, jointly-understood test objects
  - Real objects might not exhibit the same gamma spectrum
  - Up to the Host to ensure statistics are at least as good as test objects

![Graph showing calculated $^{240}\text{Pu}/^{239}\text{Pu}$ ratio vs. false alarm probability]
Understanding results

• What does an individual result mean?
  – Statistical process
  – Population determination

• Could multiple objects of different isotopic profiles present an ‘acceptable’ pass rate?
  – Motivates repeated measurements
  – But could repeated measurements reveal sensitive information?

• Also suggests the need for an agreed process for resolving ambiguous situations
  – Quarantine?
  – Re-test procedures?
Impact of operational issues

• Need to prevent tampering with items and equipment once deployed
  – Multi-day process for a single measurement
    – Sweep facility: could be multi-hour
    – Set-up & introduction of TAIs into facility: could be multi-hour
    – Initial detector cooling: 8 hours minimum
    – Measurement time of ~1 hour per measurement
  – Engineering port allows real-time download of data for debugging and analysis – needs protection

• Finite length inspections, so must also plan activities carefully

• Wider authentication requirements
  – Can we trust the detector? Onboard electronics, cooling?
  – Functional verification as yet unspecified – how do we authenticate the equipment used for that? Is COTS enough?
  – What about any other support equipment?
The “simple design” fallacy

• The UKNI assumed that a simple hardware design would be easier to authenticate than a more complex design.

• However, simplicity limits capability and data processing:
  – Computations broken into parts: not as straightforward to follow
  – Impact on deployment process
  – Harder to implement data security measures

• Simplicity is a means, not an end – transparency of design and purpose more important than ‘simple’
  – Equipment must be capable of performing tasks efficiently
  – Deep understanding of design provides basis for authentication
Where next?

- The information barrier is a research and development vehicle, not a production system – no Phase 4 planned

- BUT… others may benefit from replicating our work, studying and improving the IB hardware & software, and finding our mistakes!
  - Visit [http://ukni.info](http://ukni.info) for all the IB documentation
  - UK willing to build and donate a limited number of Phase 3b IB systems, with UK software, to interested parties who wish to use them to kick-start their own work on verification

- More broadly, there is clearly more work to be done on authentication techniques for software and hardware - access to nuclear weapons is not required to make progress here
Thanks for your attention!
Part 4

BACKUP SLIDES
What is an Information Barrier?

- A combination of **technology** and **procedures** designed to allow declared information to be verified while protecting all other information.
- The UKNI IB measures the isotopic ratio of plutonium in a test object by using gamma spectrometry, compares to pre-agreed criteria and returns a present/not proven result.
Phase 3a algorithm

- Based on collection up to 15 minutes

- $^{239}\text{Pu}$ identification
  - Five gamma peaks chosen: 345, 375, 392/393, 413, 451 keV
  - If test passed, proceed to next stage

- $^{240}\text{Pu}/^{239}\text{Pu}$ isotopic ratio
  - Limited choice due to limited $^{240}\text{Pu}$ emissions; 600 keV region chosen

- Threshold comparison
  - Ratio set to 0.1 ($^{240}\text{Pu}/^{239}\text{Pu}$)
Dounreay results

- Multiple measurements of same samples (σ not shown for clarity)

- Considerable variation in results: total counts attributed to $^{240}\text{Pu}$ is low

- Visual: under-estimation of $^{240}\text{Pu}$ content at high ratios ($^{240}\text{Pu}/^{239}\text{Pu}$ greater than 0.2)

- Linear fit appears inappropriate

- Sum results (longer count time) also suggest under-estimation of algorithm at high $^{240}\text{Pu}/^{239}\text{Pu}$ ratios

  - Spread of results consistent with PU600

\[ \text{Actual ratio} \]

\[ \text{UKNI calculated ratio} \]
Phase 3b algorithm

- Based on collection of up to an hour (up from 15 minutes)
- $^{239}\text{Pu}$ identification unchanged
- $^{240}\text{Pu}/^{239}\text{Pu}$ isotopic ratio no longer area calculation – now using peak-fitting
- Algorithm recently tested against PIDIE standards, results under analysis at present but show improved performance vs Phase 3a
- Further test & characterisation planned, results to be published on UKNI website
Peak-fitting algorithm

1. Estimate background radiation contribution for $^{241}$Am peak (662 keV)
2. Superimpose a normalised Gaussian curve onto $^{241}$Am peak
   a. Optimise curve parameters using a least-squares fit
   b. Check that the fit is good enough to validate subsequent analysis
3. Superimpose a normalised Gaussian curve onto $^{239}$Pu peak (645 keV)
   a. Optimise curve parameters using a least-squares fit
   b. Check that the fit is good enough to validate subsequent analysis
4. Calculate and subtract contributions to $^{240}$Pu peak (642 keV) from $^{239}$Pu and $^{241}$Am
   a. $^{239}$Pu at 637 keV and 640 keV
   b. $^{241}$Am at 641 keV
5. Superimpose a normalised Gaussian curve onto subtracted $^{240}$Pu peak
   a. Optimise curve parameters using a least-squares fit
   b. Check that the fit is good enough to validate subsequent analysis
6. Calculate $^{240}$Pu/$^{239}$Pu isotopic ratio using:
   a. Height of $^{239}$Pu peak (645 keV)
   b. Height of $^{240}$Pu peak (642 keV)
   c. Constant parameter, calculated from the half lives of the two isotopes, and
      the emission probability of the two gamma rays.

In order to obtain a value for isotopic ratio, the relative heights of the gamma-ray peaks from $^{239}$Pu (at 645 keV) and $^{240}$Pu (at 642 keV) are used. This value is compared with the threshold (0.1) to determine the pass/fail output.