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# 401 EMULATING VARIABLE URANIUM ENRICHMENTS WITH RADIATION SIGNATURE TRAINING DEVICES

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## ABSTRACT

Radiological signature training devices (RSTDs) are sealed sources (or assemblies of sources) that emulate the radiation signature of larger masses of special nuclear material for passive detection, while maintaining a minimal logistical footprint in terms of security, radiological safety, criticality safety, and transportation requirements. Previous work focused on emulation of large quantities of highly enriched uranium (HEU) for search and field identification with radioisotope identification detectors and mobile systems. New work has expanded into investigating use of the RSTDs with laboratory safeguards tools, such as Multi-Group Analysis for Uranium (MGAU) and FRAM, and emulating uranium spectra of multiple enrichments over more energy regions (particularly the x-ray region).

## INTRODUCTION

RSTD sources are used to generate the spectra of special nuclear material for a variety of applications that require a bright spectrum but using a large quantity of material is cost prohibitive due to security or safety concerns. Most applications of RSTDs to date have involved either testing of detectors and algorithms for search applications for material out of regulatory control or in training the use of such devices. Search instruments in this category include radiation portal monitors and hand-held radioisotope identifiers. In general, these instruments focus on the highest energy gamma rays associated with the isotope in question. There are several causes for this. First, shielding that would block most low energy gamma and x-rays is likely to exist in a search scenario. Second, Concept of Operations in search scenarios seldom requires a precision in the isotopic analysis (i.e., searchers care about the existence of HEU, not whether the HEU is 60% or 80%). During a search, the concept of operations typically requires that any HEU found outside of regulatory control is held for more detailed analysis at a later time.

Safeguards applications are different in that the goal is often to supply an immediate answer about enrichment. Some safeguards applications such as the validation of enrichment measurement algorithms require exact isotopic mixes in the measured samples. But others, such as training to quantify holdup material in pipes and tanks, do not. These applications can benefit from the portability and modularity of the RSTD sources to emulate many shapes and sizes of sources.

Most safeguards applications include inherent assumptions that the measured items are infinite attenuation thicknesses, that the sources viewed are isotopically homogenous, or a combination of both assumptions. In this work, the FRAM and MGAU algorithms are used to evaluate samples consisting of multiple sources with multiple enrichment levels and return one value for enrichment, which means these programs are not being used for their intended application.

## DISCUSSION

### Source Sets

The original HEU 25 kg equivalent sphere RSTD assembly is described in detail elsewhere [3]. The constituents of the HEU RSTD are shown in (Figure 1) and include five basic components.

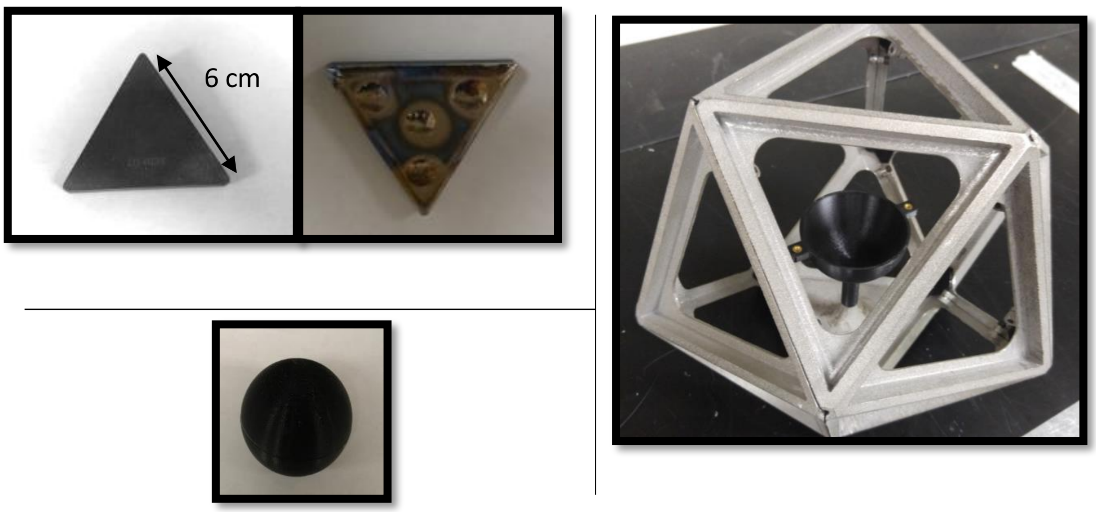


**Figure 1. Original 25 kg equivalent sphere RSTD components.** *Top left*, titanium-encapsulated triangular HEU tiles. *Bottom right*, solid metal depleted uranium (DU) core. *Right*, icosahedron frame.

**Original HEU RSTD tiles:** The outer active layer consists of 80 HEU RSTD tiles. They are titanium-encapsulated 6 cm equilateral triangular HEU sources (~3g $^{235}$U each, 93% enriched). These sources hold the $^{235}$U in a thin oxide layer that maximizes (the 185 keV) flux by minimizing self-attenuation. Using 80 small sources instead of one large source allows the flux from the $^{235}$U layer to be varied over a large range.

**DU core:** A single plastic-encapsulated 1 kg DU (0.2% enriched) metal sphere is used as the center of the assembly to supplement the 1,001 keV photon emission.

**DU tiles:** A principal limitation of the original design is a lack of variability of the depleted $^{238}$U signature due to the single large DU element. Eighty DU (6 cm) equilateral triangles (3 g each, 0.2% enriched) were produced and are shown in Figure 2. These sources were developed using rolled metal foil encapsulation in metallography resin.

**Quad triangle assemblies (QTA):** The expansion uses the original icosahedron frame but replaces the quad triangle assemblies with 20 new units, which hold up to 4 HEU triangles in an outer layer and up to 4 DU triangles in an inner layer (Figure 2).


**Figure 2. New components.** *Top left*, A single DU triangle with unique identification. *Top right*, The complete inventory of 80 DU triangles in their holders. *Bottom*, The new quad triangle assemblies hold two layers of tiles. The example shown includes one inner layer of DU tiles and one outer layer of HEU tiles

**Icosahedron frame:** This frame holds the QTAs in a roughly spherical shape with the DU suspended in the center. The purpose of the new spherical frame is to generate a radiation field that is uniform in all directions.

## Software and Detectors

Two software tools were used to analyze the assembly spectra. Note, we are not using the software as its designers intended. Both algorithms return values for the enrichment (i.e., mass percentages of $^{234}$U, $^{235}$U, $^{236}$U, and $^{238}$U), and an inherent assumption is that both of the spectra analyzed originated from a single homogenous sample. In this study, we are building the spectra by combining multiple 93% enriched and 0.2% enriched samples in different geometries. This application is outside the intended bounds of the algorithms. However, investigating how the new DU tiles and HEU tiles can be combined in various configurations to demonstrate apparent enrichment is a very useful feature of the RSTD.

## MGAU and Canberra Falcon 5000

Spectra were measured with a Canberra Falcon 5000. The Falcon 5000 is based on a planar high-purity germanium (HPGe) detector optimized for collection of low-energy gamma rays.

MGAU version 4.3 was used for this work. The standard MGAU analysis was used with a declared $^{236}$U weight percent of 0%.

MGAU [1]e is a tool kit for the measurement and determination of the uranium enrichment of a sample using high-resolution gamma spectroscopy. It is a commercial product held by Mirion–Canberra. The latest software release is version 4. The functionality and reported uncertainty of all versions have been evaluated by numerous groups in the research community. The software relies on measuring the low-energy x-ray and gamma-ray portion of the energy spectrum and performing a deconvolution peak fit function on the closely spaced photopeaks present. The analysis then extracts the uranium enrichment by performing a peak-ratio calculation based on the peak areas found by the iterative fitting routine.

### FRAM and Ortec Detective

Spectra were taken with a standard Ortec Detective. Compared with the Falcon 5000, the Ortec Detective is an HPGe detector with a higher efficiency for the collection of high-energy gammas (i.e., a coaxial geometry).

FRAM [1] version 5.2 was used for this work. FRAM was run with the HEU_Cx and LEU_Cx algorithms. The standard analysis algorithms were modified to maintain the energy calibration of the detector used. Also, the Peaks section of the Param Edit section was modified in the UHEU_Cx analysis to remove the influence and use of $^{228}$Th completely.

Compared to MGAU, the FRAM analysis uses higher energy regions of the energy spectrum and searches for isotopes other than just uranium. For example, in FRAM the predefined *_Cx analysis ranges from 120–1,010 keV.

### Measurements of NBL Standards

Each detector/algorithm combination was measured against known uranium standards to validate its performance. The standards used were the New Brunswick Laboratory Certified Reference Material (NBL CRM). Table 1 summarizes the results. The algorithm with the most accurate analysis was different for each reference material. The FRAM HEU_Cx and LEU_Cx are optimized for HEU and low-enriched uranium (LEU), respectively, and it performed best on highest and lowest enrichments. MGAU analysis performed best on the middle enrichment and estimated values higher than the reference values of the standards in all cases.

**Table 1. Summary NBL CRM measurements with the detectors and algorithms in use.**

| Standard | Reference Enrichment (mass %) | Results | | |
|---|---|---|---|---|
| | | MGAU | FRAM HEU_Cx | FRAM LEU_Cx |
| NBL-001 | 20.1 | 23.2 | 17.5 | 21.6 |
| NBL-002 | 52.5 | 61.6 | 40.1 | 33.2 |
| NBL-003 | 93.2 | 96 | 92.7 | 87.7 |

## SOURCE CONFIGURATIONS

Three geometric configurations were used for source configurations. These were two near spherical icosahedrons and one planar configuration. Multiple subconfigurations using different numbers and positions of sources were used for each. The subconfigurations were chosen to maximize the range of possible apparent enrichments.

One observation from early testing of few HEU sources in combination with a 1 kg DU solid sphere (which were the original RSTD components) was the lack of isotropicity. This was an expected result of an asymmetric configuration. The icosahedron geometry has a nearly spherical physical symmetry and results in a similarly symmetric flux distribution.

Symmetric source configurations of varied number and position of DU triangular sources were built with and without the original 1 kg DU core used in the RSTD assemblies. This change demonstrates more than just additional DU in the configurations. The core is inside all of the other layers and displays a major difference in the MGAU and FRAM algorithms. Thicker DU layers have large effects on the FRAM result but little impact on MGAU. This is due to MGAU's dependence on the x-ray region, which has a very short skin depth.

The third shape was a planar source. The planar source only used 20% of each type of triangle (16 versus 80). The principal disadvantage of a planar configuration is that it produces flux in a "dipole" shape, much brighter normal to the surface and much dimmer when viewed on edge.[1] This disadvantage is offset by many more possible permutations of DU and HEU tiles. In principle it would be possible to use 80 of each and scale the apparent enrichments on a much finer level.

## Spherical Configurations

The first group of spherical configurations used to test the versatility of the expanded source set is the basic fully loaded 25 kg HEU sphere configurations. The configuration variations documented consist of 20 QTAs, each with up to four HEU tiles and four DU tiles arranged in an icosahedron shape with a 1 kg DU sphere in the center.

Each of the QTAs is numbered from 1 to 20. The arrangement of the QTAs around the icosahedron is designed in such a way that the even and odd numbered QTAs are approximately uniformly distributed over the surface. The spherical configurations reported began fully loaded with DU and no HEU. As the configuration number increased, additional HEU tiles were added, first one to each odd numbered QTA and then to each even numbered QTA, until the four HEU slots are full (Figure 3). Next, one DU tile was removed from each even numbered QTA and then each odd until the all the DU slots were empty. This resulted in 17 spherical configurations (Table 2).

[1] Applications that require spherical symmetry are typically search applications that involve moving sources and detectors (radiation portal monitors, vehicle mounted detection system, etc). Needing to track the angle of the source as well as distance greatly increases the complexity of interpreting the results. Another application that requires symmetry is the testing of multiple detector or identification systems arrayed around a source. An asymmetric flux can create an unfair test condition and skew the results.

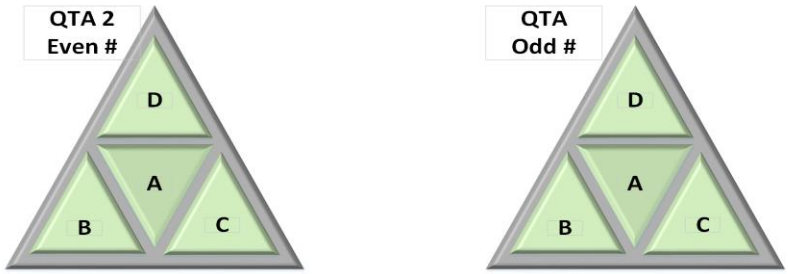


**Figure 3. Arrangement used for spherical configurations.** Sources are added alternate to the even and odd QTAs. All even QTAs are loaded identically, and all odd QTAs are loaded identically. Filled source loading locations for the even and odd QTAs are shown in Table 2.

During measurements the Falcon was located face normal to QTA14 and the Detective was face normal to QTA17 (180° opposite the Falcon, photo viewed from the detector in Figure 4. Measurements were made 1 m source center to detector face. All measurements were at least 15 minutes long. High configuration numbers were measured for longer periods (either 30 minutes or 1 hour) to reduce the statistical uncertainty (MGAU energy ratios include low-energy uranium x-rays, which become scarce in configurations with very low $^{238}$U content).

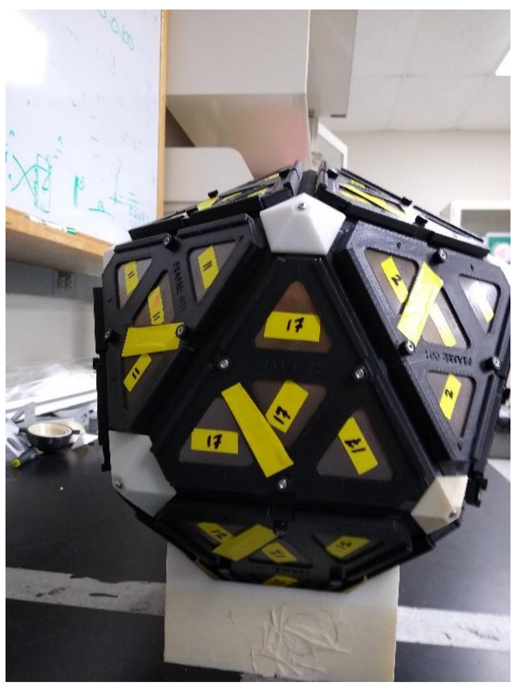

**Figure 4. Icosahedron frame, fully loaded, detective side.**

**Table 2. Seventeen spherical configurations in order of increasing apparent enrichment.** Geometry of the locations is shown in Figure5. Locations denoted in blue are filled with a DU tile. Locations denoted in green with a HEU in front and a DU behind. Locations denoted in gold with only an HEU tile.

| **Position** | **A** | | **B** | | **C** | | **D** | |
|---|---|---|---|---|---|---|---|---|
| **QTA#** | **Odd** | **Even** | **Odd** | **Even** | **Odd** | **Even** | **Odd** | **Even** |
| **Config** | | | | | | | | |
| 1 | blue | blue | blue | blue | blue | blue | blue | blue |
| 2 | green | blue | blue | blue | blue | blue | blue | blue |
| 3 | green | green | blue | blue | blue | blue | blue | blue |
| 4 | green | green | green | blue | blue | blue | blue | blue |
| 5 | green | green | green | green | blue | blue | blue | blue |
| 6 | green | green | green | green | green | blue | blue | blue |
| 7 | green | green | green | green | green | green | blue | blue |
| 8 | green | green | green | green | green | green | green | blue |
| 9 | green | green | green | green | green | green | green | green |
| 10 | green | green | green | green | green | green | green | gold |
| 11 | green | green | green | green | green | green | gold | gold |
| 12 | green | green | green | green | green | gold | gold | gold |
| 13 | green | green | green | green | gold | gold | gold | gold |
| 14 | green | green | green | gold | gold | gold | gold | gold |
| 15 | green | green | gold | gold | gold | gold | gold | gold |
| 16 | green | gold | gold | gold | gold | gold | gold | gold |
| 17 | gold | gold | gold | gold | gold | gold | gold | gold |

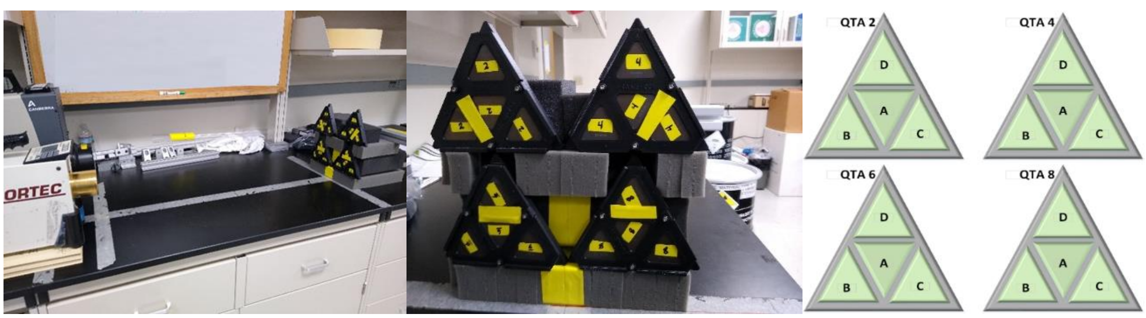


**Figure 5. Planar measurement setup.** *Left*, Detectors and sources. *Center*, Planar array fully loaded. *Right*, There are 16 locations in four QTAs. Each can be filled with either an HEU tile, a DU tile, or both.

## Planar Configurations

Four QTAs (#2, #4, #6, and #8) were used in the planar configurations. They were arranged in a vertical plane (Figure 5). The configurations begin with the array fully loaded with DU. HEU tiles were filled one by one until all are full. Then DU tiles are removed one by one until all are empty, which results in 33 planar configurations (Table 3).

The planar source configuration was placed 2 m from the detector (detector face to source center). The detector centers for the Falcon and Detective were each offset 15 cm left and right from the center of the source array to allow simultaneous measurement.

**Table 3. Planar configurations.** Geometry of the locations is shown in Table . Locations denoted in blue are filled with a DU tile. Locations denoted in green with a HEU in front and a DU behind. Locations denoted in gold with only an HEU tile (continued).

| | A | | | | B | | | | C | | | | D | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **QTA#** | **2** | **4** | **6** | **8** | **2** | **4** | **6** | **8** | **2** | **4** | **6** | **8** | **2** | **4** | **6** | **8** |
| **Config** | | | | | | | | | | | | | | | | |
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## RESULTS

Apparent $^{235}$U mass % is plotted in Figures 6–8. MGAU results span 0% to approximately 96% apparent enrichment for all three configuration sets. FRAM results for the sphere configurations without the core span 0% to 96%. FRAM results for the sphere configurations with the core span

0% to ~59%. This difference is due to the FRAM algorithm's use of higher energy gammas, which have a higher flux in the with core configurations.

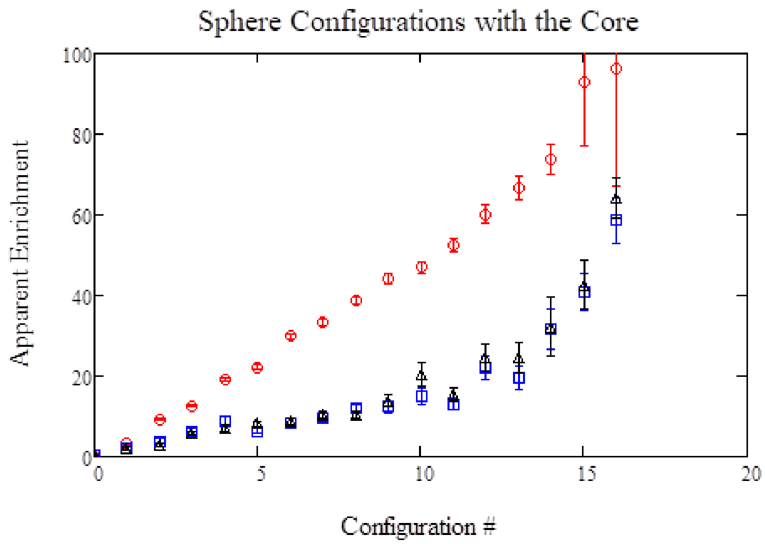


**Figure 6. Analysis results for sphere configurations with the DU core.** Red circles are MGAU, blue squares are FRAM HEU, and black triangles are FRAM LEU.

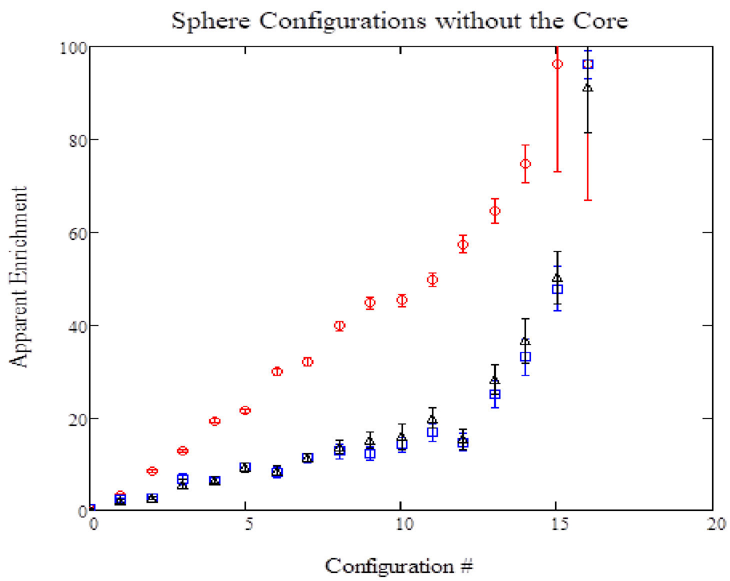


**Figure 7. Analysis results for sphere configurations without the DU core.** Red circles are MGAU, blue squares are FRAM HEU, and black triangles are FRAM LEU.

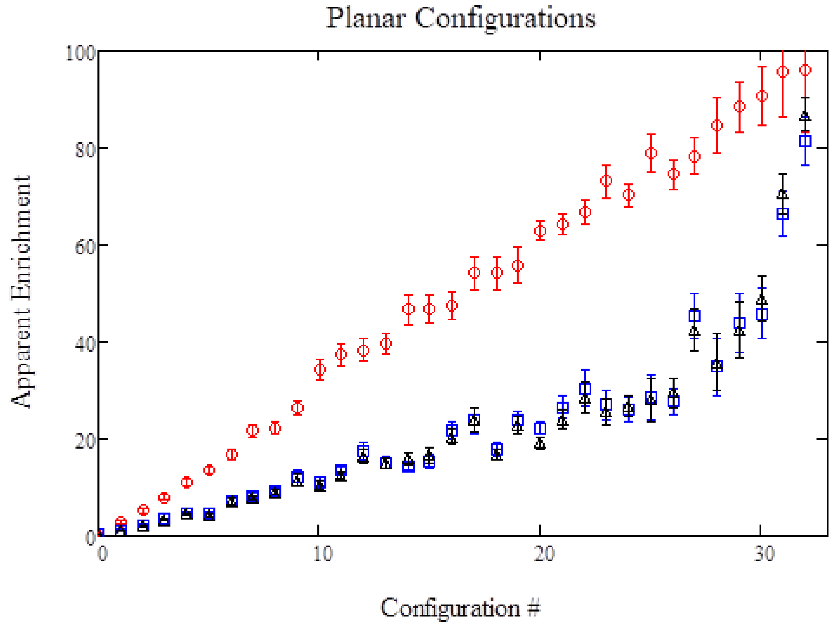


**Figure 8. Analysis results for planar configurations.** Red circles are MGAU, blue squares are FRAM HEU, and black triangles are FRAM LEU.

Note, the reported relative uncertainty increases for configurations with lower quantities of DU and is quite large for the final points.

## CONCLUSION

Used, the HEU and DU RSTDs can be used to mimic a large variety of uranium enrichments from 0.2% to 96% when viewed using FRAM or MGAU. Because FRAM and MGAU employ different regions of the spectrum to perform their analysis and because RSTDs are not infinite thickness samples, any given configuration of RSTD tiles will generate different results in the two algorithms.

## REFERENCES

C. Blessinger, J Garrison, and M. Dion. “Radiation Signature Training Device Gamma Equivalent Spheres.” 1314, INMM 61st Annual July 12–16, 2020.