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Testing the Ortec's Isotopic and Eberline's Snap software for Uranium waste measurements

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Abstract

Uranium enrichment plants normally generate lots of wastes. The wastes are in various matrices such as clothing, glass, concrete, aluminum, and steel, etc. They are in the quantity of a few grams to many kilograms and generally stored in 55-gallon drums. For accountability, it is important to determine the amount of uranium in the waste drums to a certain level of accuracy. There are several commercially available systems that can accurately determine the uranium mass in the waste drums, such as Tomographic-Gamma-Scanner¹ (TGS) or Segmented Gamma-Ray Scanner² (SGS). However, those systems are too cumbersome and expensive. Cheap and simple single detector systems are also available commercially from several companies. The workhorse of these systems is the software, which would work with any germanium detector system. We mocked up waste drums containing several hundred grams to several kilograms of uranium with different isotopic compositions in various matrices. We acquired data using a coaxial germanium detector. We tested two different software codes from two companies, the Ortec's Isotopic software and the Eberline's Snap software. The results with the germanium detector were very encouraging, which led us to test with the NaI detectors. The NaI detectors have much worse resolution than the germanium detectors. However, they are very cheap, can be very large in detector size and, thus, efficient for a given counting time, and are simpler because of not requiring liquid nitrogen for cooling. The results, advantages, and disadvantages of the two software codes and the two detector systems will be discussed.

Keywords: uranium; waste; assay; isotopic.

1. Introduction

Nuclear waste measurement and analysis is a difficult process and it is often difficult to obtain accurate results. Wastes are stored in containers, typically the 55-gallon drums. They are normally sealed and the containment may be known, though not in great detail. For some nondestructive assays (NDAs) using gamma rays such as isotopic analysis, the exact composition of the material and the matrix may not be necessary in order to obtain good results. For some other NDAs using gamma rays, such as the nuclear waste assay techniques, the exact or almost exact composition of the nuclear material and a matrix and a container may become very important.

The TGS and the SGS use a germanium detector with a transmission source to determine the corrections due to the self-absorption in the nuclear sample and the absorptions due to a matrix and a container. These two methods have shown reasonable accuracy in their determinations of the

masses of the nuclear isotopes, with typical bias of about 10% depending on the mass, container, and the matrix¹⁻². These systems are commercially available in various sizes to accommodate a wide range of waste measurements. The main disadvantage of these two systems is that they are too cumbersome and expensive.

There are some other simpler systems or techniques commercially available through several manufacturers that can analyze waste and determine the mass of the nuclear material embedded in the waste. These simpler systems use a single germanium detector without transmission source. For some of those systems, an optional transmission gamma source may be used for better estimation of the nuclear source and the matrix. These simple systems give much less accuracy than the TGS and the SGS systems but are much cheaper and much simpler to operate.

Our goal of this work was to find the most practical method to estimate with acceptable uncertainty the mass of uranium waste stored in 55-gallon drums. The uranium in the waste is mainly low-enriched uranium (LEU) in the quantity of few grams to many

kilograms. The TGS and the SGS were not considered seriously due to the cost of the systems and operation. We, therefore, resorted to using a simple waste assay system from a commercial vendor or developing our own waste analysis system based on our isotopic analysis software, FRAM³⁻⁴. After time and cost budget considerations, we decided to test some of the commercial software codes. If they or one of them would be deemed satisfactory, then we would use available commercial codes for our uranium waste assay system; otherwise, we would have to quickly develop our own code.

2. Hardware and software

2.1. Detectors and electronics

The detector used in the test was a high-purity germanium (HPGe) coaxial detector cooled with LN₂ and manufactured by Ortec with a relative efficiency of about 50%. The detector was shielded from the side with a 1.25" thick tungsten collimator and from the back with a 0.5" thick tungsten plate to reduce background gamma rays.

The electronic system was the DSPEC Plus, a digital multichannel analyzer (MCA) manufactured by Ortec. It was connected to the PC computer, running Windows NT, by ethernet.

2.2. Containers and sources

A variety of LEU and one high-enriched uranium (HEU) samples were tested. They were:

- One 200g Oxide can, 0.71% U-235.
- One 200g Oxide can, 1.94% U-235.
- One 200g Oxide can, 4.46% U-235.
- One 230g Oxide can, 20.11% U-235.
- Three 1000g Oxide cans, 0.71% U-235.

We used 55-gallon containers containing three different matrices to test the matrices effect: one was empty, one contained polyethylene beads, and one contained glass rings. We also tested the position effect by placing sources in various radial and vertical positions inside the containers. The drums were set on a rotating platform. Most of the measurements were done with the drums rotated.

2.3. Software

We used two different waste assay software codes developed by two vendors: Isotopic by Ortec and Snap by Eberline. In addition to these two waste

assay software codes, we also used three other codes to acquire spectra and to extract peak information, which feeds Isotopic/Snap for detailed analysis. The code Gamma Vision was used for data acquisition with the DSPEC Plus and for extracting peak and detector information to be used with the Isotopic software. Similarly, the Maestro code was used to extract peak information to be used with the Snap software. The isotopic analysis code FRAM developed by Los Alamos National Laboratory (LANL) was used to determine the isotopic composition of the test samples using waste assay measurement data. The isotopic information was then used as an input for analyses in the Isotopic code. The results in Isotopic, when the isotopic information from FRAM was used, were then compared with those when we assumed no isotopic information was known and when the certified isotopic composition information was used.

2.4. Data acquisition

We tested three drums separately. For each drum, we put sources in various positions inside the drum. Only one type of enrichment material can be inside the drum at a time. That is, for three sources with enrichment of 1.94% and above, only one source can be placed in the drum at a time for the measurements. For the four natural uranium sources, they all could be measured individually or together in various positions inside the drum. The data were acquired at two different distances. The distances from the drum center to the detector's front face were 78 cm and 120 cm.

We started out with two different kinds of measurements: one with the drum standing still and one with the drum rotated slowly (about 0.5 rpm). We measured a number of spectra and quickly compared the results using the Isotopic software. It was as we expected: the results from the non-rotating drum are very dependent on the position of the source inside the drum and their overall results are much worse than those with the rotating drum. The rotation of the drum would average out the dependency on the radial distance of the source inside the drum and reduce the bias. So for the rest of the test, we only acquired the data with the drum rotated.

3. Analysis

Both the Isotopic and the Snap software codes require accurate absolute efficiency of the detector. We used a ¹³³Ba source, a ⁵⁷Co source, a ⁶⁰Co source, and a ²⁰⁷Pb source with known activities

together to obtain peak intensities of a wide energy range of peaks. We then calculated the detector efficiency curve from the obtained peak intensities.

Figure 1 shows a typical spectrum and the absolute detector efficiency for point sources at 120 cm distance. The two marked peaks are the 186-keV peak of ^{235}U and 1001-keV peak of ^{238}U . The data points and the curve of the detector efficiency are extended up to 1.33 MeV. However, the efficiency curve is shown only up to 1023 keV in the graph.

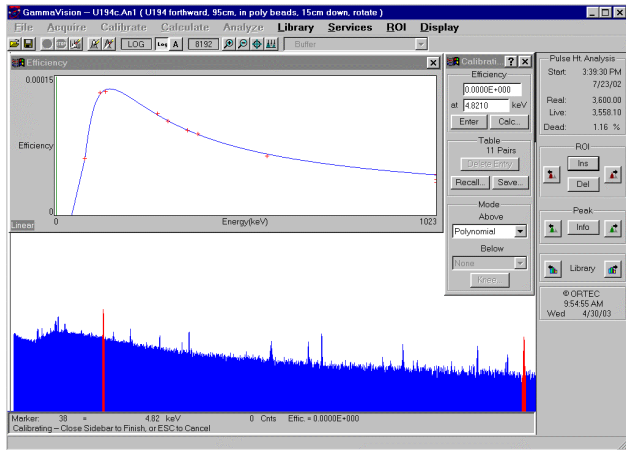


Figure 1. A spectrum of a LEU source in polyethylene beads. The upper plot shows the absolute detector efficiency for point sources at 120 cm distance.

3.1. Ortec's Isotopic

There are 2 main parameters in Isotopic software that one needs to adjust: matrix density and weight fraction of uranium in the container. Figure 2 shows a typical adjustment plot in Isotopic. The matrix density and uranium weight fraction can be adjusted using the sliding bars or by typing in the numbers in the text boxes. The data points on the plot and the ^{235}U enrichment results (in the enrichment box) will vary accordingly.

The container thickness can also be adjusted. However, since the container thickness is normally known to a high degree, it appears that one should just use the exact known value of the container thickness instead of trying to adjust it to obtain the results.

One can see from figure 2 the peaks used for the analysis. They are 144-, 163-, 186-, and 205-keV peaks for ^{235}U and 743-, 766-, 946-, and 1001-keV peaks for ^{238}U . Only the 186-keV and the 1001-keV peaks are used in determining the ^{235}U enrichment.

The other peaks are used to help the user judging the adjustment in the eyeball method.

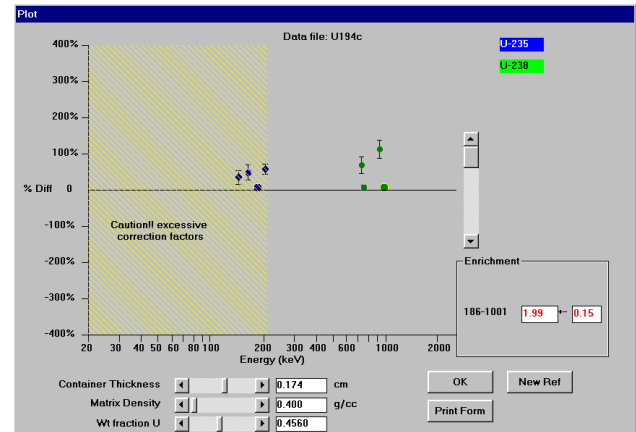


Figure 2. The adjustment plot of the Isotopic software.

For the analysis, we first tried to adjust both the matrix density and uranium weight fraction at the same time in order to determine the best parameters for each measurement. We soon found that it would be impossible to find the relationship between the parameters or the best parameters for each measurement when both parameters are allowed to vary simultaneously. We then set one parameter fixed and adjusted the other until one of the three criteria for optimal results was met. That is, when we adjusted the matrix density to obtain the best results, we kept the uranium weight fraction at the constant value of 88%. The value 88% is roughly the uranium weight fraction in uranium oxide. Note that in a typical waste measurement where waste may be distributed somewhat homogeneously throughout the whole container, the uranium weight fraction will probably be much lower. When the uranium weight fraction is adjusted, then the matrix density is kept constant. We used the constant matrix densities of 0.1 g/cm^3 for the empty drum, 0.4 g/cm^3 for the drum containing the polyethylene beads, and 0.9 g/cm^3 for the one containing glass rings. These are roughly the overall densities of those drums.

As mentioned above, with one of the parameters fixed, we adjusted the other parameter until one of the criteria for best results was met, then we would stop the adjustment and accept the results. That is, we can eyeball the adjustments so that the data points on the adjustment curve are about right or adjust the parameters until the enrichment agrees with the known or accepted value. The eyeball judgment method is more or less an art and it depends somewhat on the user. Different users may see the adjustment curve somewhat differently and

may judge somewhat differently when the curve is at its best. This means that two different people analyzing the same data may give different results using this method.

As for the other method of analysis where the adjustment is done until the enrichment agrees with the accepted value, the results do not depend on the user but do depend on the accuracy of the accepted enrichment. If the known or accepted enrichment value is not very accurate then the results may not be very good. The known or accepted value can be provided from reference books or determined from some isotopic analysis software. We used both the certified enrichment values of the sources and the enrichment values determined from the isotopic

analysis code FRAM. When the isotopic results from FRAM were used, then we first used FRAM to analyze the spectrum to obtain isotopic information of that spectrum. That isotopic or enrichment result was then used as the accepted enrichment value for the Isotopic waste assay software.

Figures 3 and 4 show the results of using Isotopic from three different analyses for ^{235}U and ^{238}U . We can see that when the accepted or certified enrichment values are used, then the results (of both ^{235}U and ^{238}U) appear to be the best. It is difficult to say which one is better, the eyeball method or the FRAM input value method. We, however, recommend the FRAM input method because it does not depend on the judgment of the user in the

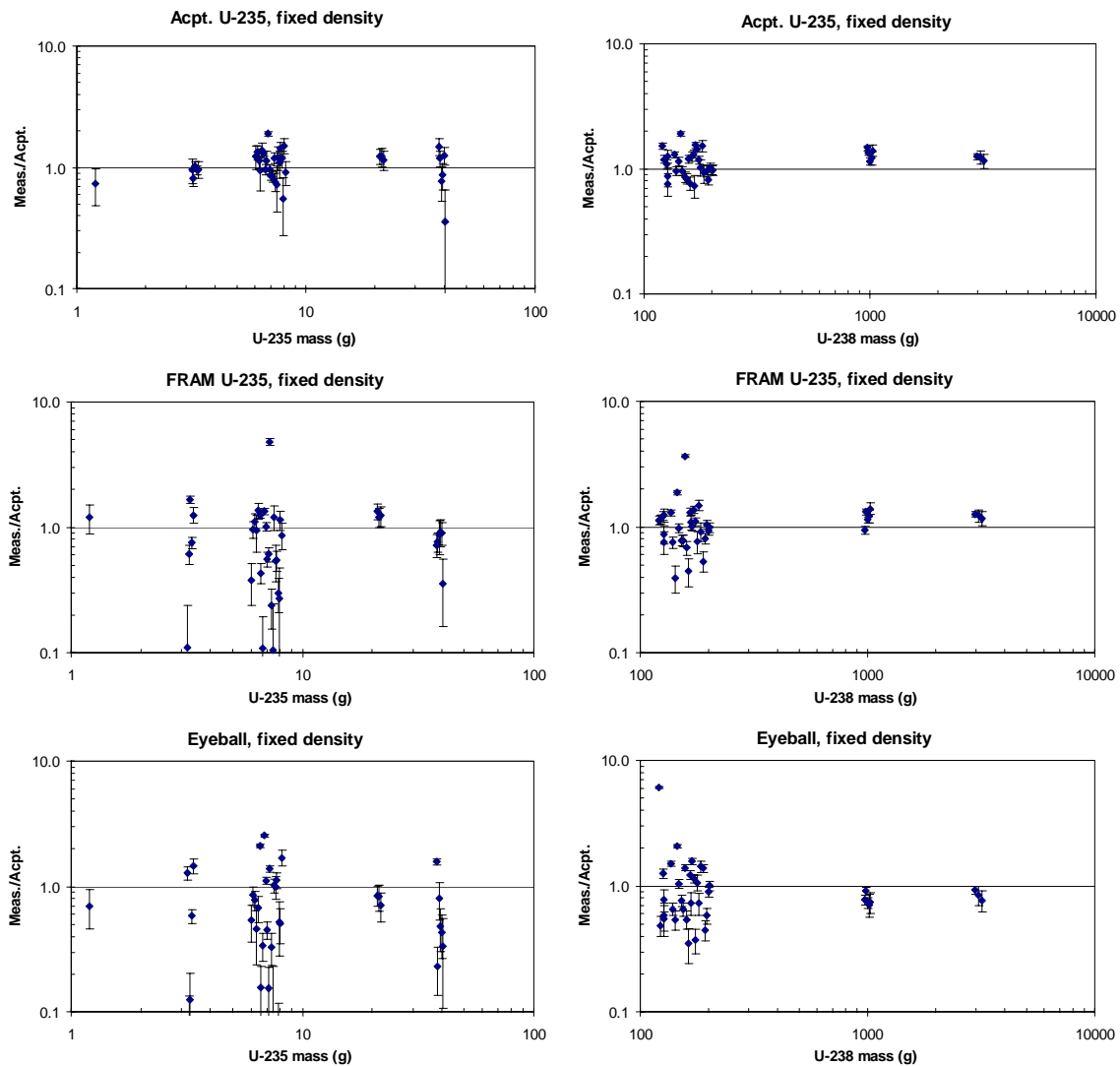


Figure 3. U-235 and U-238 results for the three methods with the matrix density fixed and the uranium weight fraction varied. The error bars are 1 sigma uncertainties reported by Isotopic.

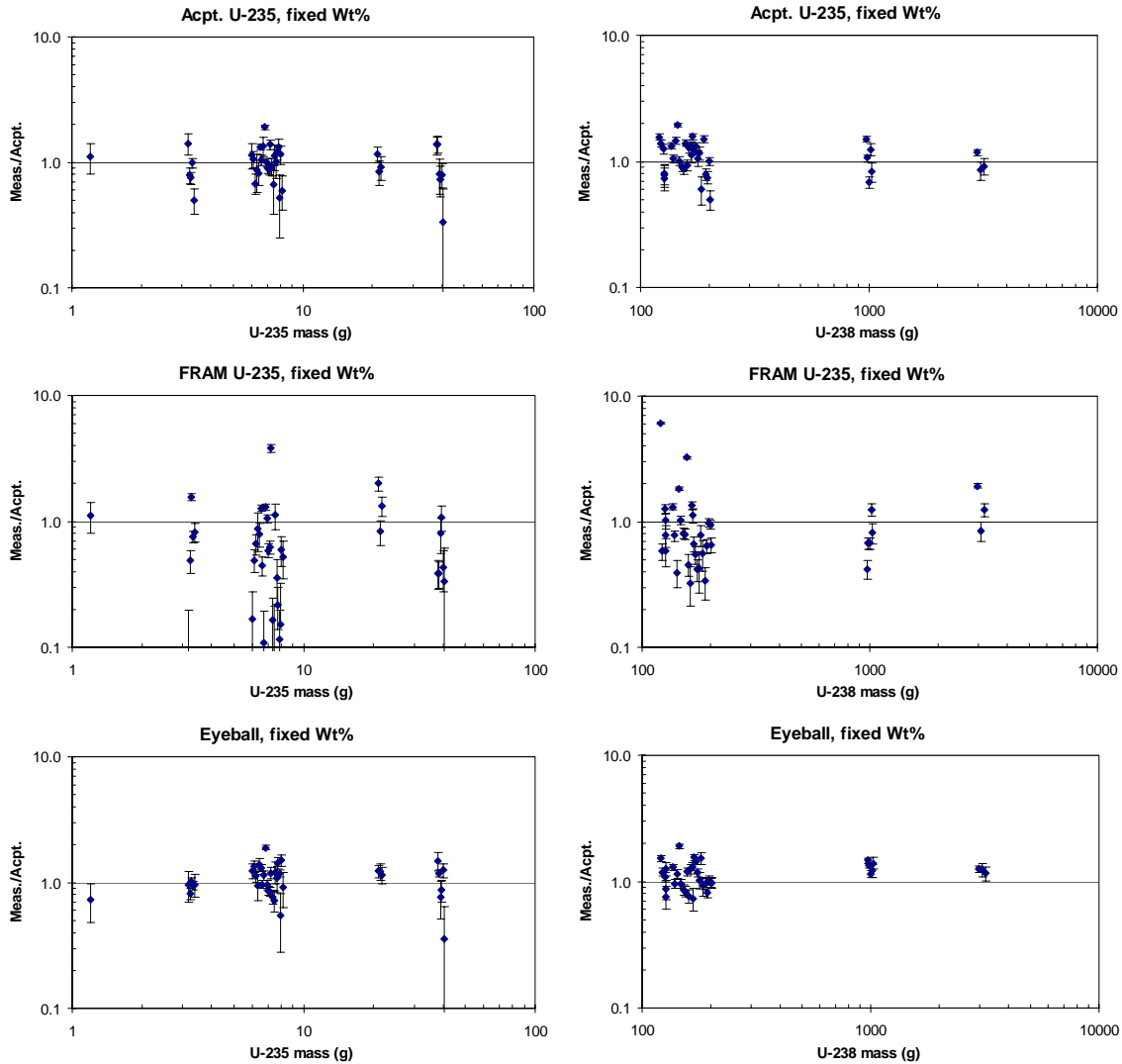


Figure 4. U-235 and U-238 results for the three methods with the uranium weight fraction fixed and the matrix density varied. The error bars are 1 sigma uncertainties reported by Isotopic.

analysis.

Comparing the results when the matrix density is fixed with those when the uranium weight fraction is fixed, we see that they appear to be very much the same. After examining the results carefully, we conclude that the results with the fixed matrix density may be a bit better even though it may not be significant.

Examining data points in the plots in figures 3 and 4, we see that a large fraction of the points are far outside the expected measurement/accepted ratio of 1. Some points are even more than 10 times the reported standard deviations away from the expected results. This is probably due to two factors:

the mockup drums do not exactly represent the real waste drums, and the Isotopic code might have underestimated the uncertainties of the results.

Table I shows the overall reported uncertainties and the actual or calculated uncertainties (from all the measurements) of the results. The reported errors are believed to be random errors only and do not include systematic errors.

The second and fifth data columns in Table I show the average of the reported uncertainties of ^{235}U and ^{238}U from the Isotopic software. One may note that uncertainties of ^{238}U obtained from Isotopic are very consistent with different analysis methods.

Table I. Average uncertainties of the results.

Method	U-235 Isotopic %STD	U-235 actual %STD	U-235 actual/Isotopic	U-238 Isotopic %STD	U-238 actual %STD	U-238 actual/Isotopic
Accepted U-235, fixed density	18.6	31	1.7	10.3	27	2.6
Accepted U-235, fixed wt%	18.0	29	1.6	10.3	37	3.6
FRAM U-235, fixed density	16.0	72	4.5	10.3	33	3.2
FRAM U-235, fixed wt%	14.8	82	5.5	10.3	49	4.8
Eyeball, fixed density	14.2	93	6.5	10.3	35	3.4
Eyeball, fixed wt%	15.7	89	5.7	10.3	46	4.5

The third and sixth columns show the standard deviations (STDs) determined from the spread of all the results. These standard deviations are more believable than those reported from the code. The fourth and seventh columns show the ratios of the actual STDs to the reported STDs. One may say that for each method, the Isotopic code underestimates the uncertainties by a factor shown in column fourth or seventh.

3.2. Eberline's Snap

The same data were also analyzed using the Snap software. There is one main parameter (lump correction) that the user needs to adjust. There is no option for matching the enrichment as in Isotopic. This is a disadvantage compared with that of the Isotopic software. However, this code has some other options that may prove to be useful or better than the Isotopic code in some circumstances.

Snap does let you model your own matrix. If the matrix is accurately known then one can specifically model every point in the drum (or container) for better results. The weakness of modeling the whole matrix is that it is very time consuming and it requires an expert. Also, in the real world, one may know the matrix of a drum or container in general but not enough in detail for specific modeling of the whole drum. So for this test, we did not use the specific modeling even though we know the matrix in detail and can accurately model it.

The Snap code also has the option to compensate for absorption by the sources and the matrix using a transmission correction source. The weakness of this transmission correction is that it would make the system more complicated and the acquisition time longer since one has to measure the transmission data to do the correction.

Figure 5 shows a typical adjustment plot in Snap. There is only the lump correction parameter that can be adjusted. The lump thickness is adjusted until the designed result is achieved. We can eyeball the adjustments so that the data points on the adjustment curve are about flat or when they stop changing (infinite thickness).

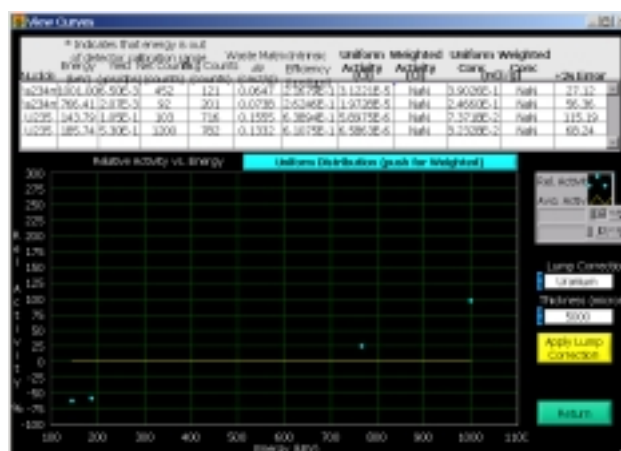


Figure 5. The adjustment plot of the Snap software.

One can see that Snap uses only four peaks for the analysis instead of eight peaks like the Isotope software. They are 144- and 186-keV peaks of ²³⁵U and 766- and 1001-keV peaks of ²³⁸U. The other four peaks are less intense and are not used. The reason for not using the weaker peaks is due to the capability of the software used to analyze the gamma ray peak.

Snap can read the output from Maestro software but not the Gamma Vision output. Maestro uses only simple region of interest (ROI) method to determine the areas of the peaks in a spectrum. This method works fine for good, intense, stand-alone peaks. However, most of the measured spectra are poor and the intensities of those four peaks are weak. The

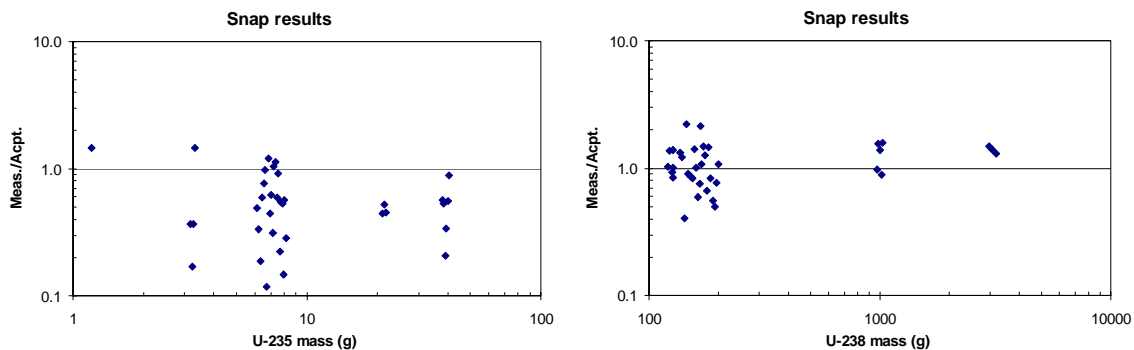


Figure 6. U-235 and U-238 results for the Snap method. The error bars are too large and are omitted in these figures.

ROI method does not work well with these weak peaks so we did not use those peaks with Snap.

Note that, the Isotopic code uses the output from Gamma Vision. Gamma Vision uses least-square fits to determine the areas of the peaks so it does not have problem extracting peak areas from weak peaks like the ROI method.

Figure 6 shows the results of the Snap waste assay software. We see that Snap tends to underestimate the ^{235}U mass, especially the larger mass, while for ^{238}U , its results seem to be reasonable. We did not plot the error bars in these graphs because they are too large and would make the graphs too crowded.

Table II shows the overall Snap reported uncertainties and the calculated or actual uncertainties (STD from many measurements) of the results. From the table, we can see that the Snap reported errors for ^{235}U are much larger than that of the actual or calculated errors. This is because the Snap uncertainties include both the random and systematic errors, while the calculated errors shown in the table are just from the random errors only.

Table II. Average uncertainties of the results.

Isotope	Snap %STD	Actual %STD	Actual/Snap
U-235	260	65	0.25
U-238	62	65	1.05

Reexamining the first graph in figure 6, we can see that the ^{235}U results are underestimated by an average factor of about two or three. This bias of several hundred percents is reflected in the large reported uncertainty of ^{235}U shown in Table II.

For ^{238}U , we can see from the second graph in figure 6 that it is relatively bias-free or the bias is small. This is also reflected by the reported error shown in Table II where it is about the same as the calculated random error.

4. NaI measurement and analysis

After we acquired the waste data with an HPGe detector and then analyzed them using two different software codes and several different methods, we found that only the first two methods from the Isotopic code are sufficiently accurate for our project. Both methods require the enrichment to be accurately known (much better than that obtained with an isotopic analysis code such as FRAM). This requirement may pose a great challenge for some project but luckily for our project, the enrichments of the uranium wastes are known. So we decided to use either one of these methods or some combination of both methods (Isotopic using accepted ^{235}U enrichment) for our project.

However, after seeing that these two methods require (beside the known enrichment) for uranium assay only the peak areas of the 186- and 1001-keV peaks in a spectrum, we thought that these methods might work with spectra obtained with a NaI detector.

In typical waste assay gamma ray measurements, the intensities or areas of a large number of peaks are required for good analysis. Therefore, an HPGe detector naturally becomes the first or only choice due to its excellent resolution and reasonable efficiency. Some other types of detectors such as NaI or BGO, etc., may have better efficiency but do not have enough resolution to resolve nearby peaks for analysis.

Our project of determining the uranium waste is a special case where a NaI detector may work. First, the uranium enrichment of the waste is known so that we can use isotopic with a known enrichment method. This method requires only the peak areas of only two peaks, which may be possible for a NaI detector. Second, uranium does not have many intense gamma rays and most of its gamma rays are well separated. The two most intense gamma rays separated by a wide energy gap in LEU are the 186 keV from ^{235}U decay and 1001 keV from ^{238}U - ^{234}Th - ^{234}Pa decay. The intensities of these two gamma rays can be easily obtained with a NaI detector. So we decided to test the uranium waste assay with the NaI detector.

Actually, using a simple region of interest (ROI) method as that in Maestro, one cannot separate the 186-keV peak from the 163-, 202-, and 205-keV peaks and would have to settle for the total combined intensity of all ^{235}U peaks from 163 keV to 205 keV. The Gamma Vision software is somewhat more complicated and uses least-squares fits to determine the peak areas. So it is able to separate the other peaks from the 186-keV peak and give the peak areas for all the intense peaks in that bundle.

4.1. Detector analysis

We first tested a large number of available NaI detectors from small to large, including an unusually long 2"x22" NaI detector, in order to find one most suited for the job. We finally settled for a reasonably large 4"x4"x5" detector made by Alpha Spectra, Inc. Its resolution is 7.9% at 662 keV with the Dart MCA manufactured by Ortec running at 2 μs shaping time. In the uranium measurements, it was shielded from the side and the back with 2"-thick lead bricks to reduce background gamma rays entering the detector.

We used a large number of peaks from a large number of sources with known activities to determine the efficiency of the detector. The four sources used for the efficiency determination were ^{60}Co , ^{207}Bi , ^{133}Ba , and ^{152}Eu . Each of these sources was measured separately, and the peak areas of the peaks of each source were obtained separately. All the peak intensities of all five sources were then combined to determine the detector efficiency.

4.2. Uranium sources

We used four different LEU sources for the test. They are:

- One 1000g Oxide can, 0.71% U-235.

- One 200g Oxide can, 1.94% U-235.
- One 200g Oxide can, 2.95% U-235.
- One 200g Oxide can, 4.46% U-235.

4.3. Acquisition and analysis

We used the same three 55-gallon containers as with the HPGe measurement for the NaI test: empty, polyethylene beads, and glass rings matrices. The sources were also put inside the drums at various radial and vertical positions and the drums were rotating when the data were acquired like that with the HPGe detector. The distance from the drum center to detector front face was 69 cm. The measurement time was one hour for each spectrum.

With these small uranium sources at a somewhat large distance from the detector, the gamma-ray signals from such sources are not much more intense than those from the surrounding background (BG). With the HPGe detectors, we do not care much for the BG because we can always resolve the uranium peaks from the BG peaks. However, for the NaI, with its much worse resolution, it cannot resolve the uranium peaks from the BG peaks. Therefore, it is important that the background is properly subtracted so that the uranium peaks are properly determined. So we obtained an overnight spectrum of the BG. This spectrum is used to subtract the BG from the spectra.

The NaI spectra tend to drift a lot so we set the gain stabilizer on the natural occurring 1461-keV peak of ^{40}K . K-40 is a naturally occurring isotope and the 1461-keV peak is seen everywhere. Its activity is just intense enough to set the stabilizer on it for good stabilization. Using this peak for stabilization has the advantages that it is in a clean region and does not interfere with uranium peaks, and it or its parent isotope ^{40}K is easily obtained. If the detector were shielded so well that no 1461-keV peak from the background could get into the detector, then one could always obtain a small amount of potassium salt or fertilizer and set it near the detector to use as the source for the 1461-keV stabilization peak. For stabilizing electronic drifting, this peak is better than the 1001-keV peak of ^{238}U in real waste measurements because for some drums, the intensity of this 1001-keV peak may be very weak or nonexistent such that the stabilizer may not work properly.

Figure 7 shows a typical LEU spectrum acquired with the NaI detector and the absolute detector efficiency for point sources at 72 cm distance. The upper spectrum is original. The lower spectrum is the BG

subtracted spectrum. The marked peaks are the 186-keV peak of ^{235}U , the 766- and 1001-keV peak of ^{238}U , and the 1461-keV peak of ^{40}K from the BG.

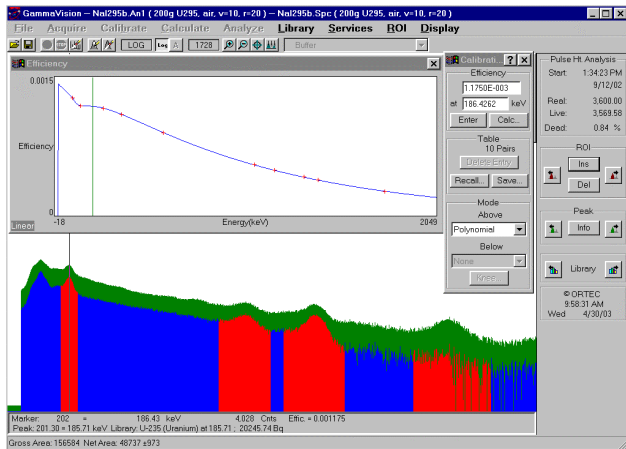


Figure 7. A spectrum of a LEU source in an empty drum. The upper spectrum is original. The lower spectrum is the BG subtracted spectrum. The efficiency plot shows the absolute detector efficiency for point sources at 72 cm distance.

The efficiency curve shows an unusual bend at about 120 keV. This means that the efficiency below 120 keV is probably not correct. This, however, does not cause any problem for the uranium waste

measurement because the lowest energy peak used is at 144 keV, which is much higher than the 120-keV limit.

Figure 8 shows the results of the NaI waste assay system using Isotopic with the uranium enrichment known. A quick look at the graphs would reveal that the fixed density/varying uranium weight fraction method is much better than the other method. It is better in both the average bias and the uncertainty. The fixed density method has a small bias and the random errors appear to be small, while the fixed uranium weight fraction method has very large bias, underestimates the mass of most of the samples, and its results appear to scatter more.

Table III shows the overall reported uncertainties and the actual uncertainties of the results. We can see that the actual errors of both ^{235}U and ^{238}U are reasonable for the fixed density method. They are actually about the same or even slightly better than those measured with the HPGe detector. The average bias is about 10% too low for both ^{235}U and ^{238}U . This is not a large bias considering the large random uncertainties of the measurements. However, since we know the bias of the system, we can systematically correct for it if we design.

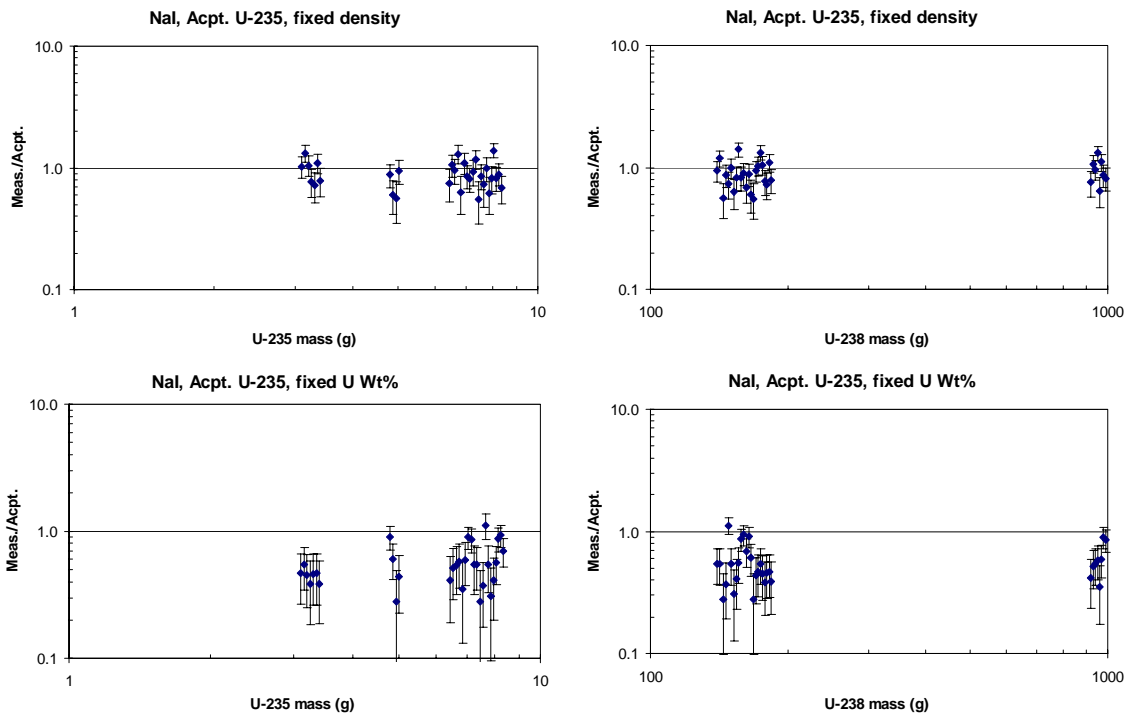


Figure 8. U-235 and U-238 results for the fixed density/varying uranium weight fraction method and the fix uranium weight fraction/varying matrix density method. The error bars are 1 sigma uncertainties reported by Isotopic.

Table III. Average uncertainties of the results.

Isotope	Isotopic %STD	Actual %STD	Actual/Isotopic
U-235 fixed density	20.4	26	1.3
U-238 fixed density	17.8	27	1.5
U-235 fixed U wt%	20.4	55	2.7
U-238 fixed U wt%	17.8	56	3.1

5. Discussion

We tested two waste assay analysis software codes developed by two commercial vendors on mocked up 55-gallon uranium waste drums. We employed all the possible methods of analysis of the Isotopic software, including using the NaI detector for analysis. In reality, the Isotopic software was designed to analyze data from an HPGe detector only and not for NaI detector analysis. Even the Gamma Vision software, which we used to obtain the peak areas from the spectra, are designed for HPGe only. We had a hard time accurately extracting the peak areas from the NaI spectra. We only employed the technique with NaI because we thought that it could work and indeed it did work quite well.

The Snap software has two useful options, which may improve the analysis: matrix modeling and transmission correction. We, however, did not employ those options because our goal was to find as simple a waste assay system as possible. If we employed one or both of those options then the system will become complicated and difficult to use. So we omitted those options in our test.

The Isotopic software appears to report only the statistical or random uncertainties. These reported uncertainties are much smaller than actual spread from multiple runs. To correctly obtain the uncertainties, one may need to multiply the reported uncertainties with some factor (determined from multiple measurements).

The reported uncertainties from the Snap software appear to include both the statistical and the systematic uncertainties. They seem to reasonably represent the true errors of the measurements. The only problem with them (and with the Snap software) is that the size of errors is too large and for any result with such large error, it is almost useless.

The methods that use the accepted enrichment (with both Ge and NaI detectors) and fixed density give the best results, about 30% STD for both ^{235}U and ^{238}U . Also, a large NaI detector can give equivalent

or better results than an HPGe detector when used with Isotopic software and known enrichment uranium.

A NaI detector has many advantages compared to an HPGe detector such as:

- Inexpensive
- Simple
- Requires no maintenance (no liquid nitrogen)
- Can be very large and efficient.

It, however, also has many disadvantages, such as:

- Difficult to extract peak areas from the broad NaI peaks using Gamma Vision, as in this test. The ScintiVision software from Ortec or Genie 2000 from Canberra may be the better choices, but we haven't tried them yet.
- Due to low resolution, interference from other isotopes can give bad results.

6. Acknowledgments

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