Larger Volume Detector Efficiency Parameterization with the MGA Code

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Abstract

The Multiple Group Analysis (MGA) code is widely used for the non-destructive determination of the relative isotopic composition of plutonium items. The MGA method is based solely on the analysis of the gamma-ray spectrum recorded using a high resolution gamma spectrometer. The form and function of the code has evolved greatly since its origins in the 1980's. Over the lifetime of the code there have been tremendous developments in detector technology. The small volume planar Low Energy Germanium (LEGe) detectors available for safeguards work in the early years have given rise to the use of large volume Broad Energy Germanium (BEGe) detectors today in many applications - including the challenging arena of nuclear waste assay. Certain algorithms within MGA have been hardened to meet this challenge and the code is now more robust to poor counting statistics and poorer pulse height resolution as a consequence. The universe of applications to which MGA is being applied is constantly growing. These applications frequently step outside the initial expectations of the code and/or of the technical boundaries of the day. In particular we address here the functional form used within MGA to describe the energy dependence of the relative full energy peak efficiency curve of the Ge detector. The relative efficiency curve is represented by the product of three terms. The filter attenuation factor and self-attenuation factors together modify the basic response function of the Ge crystal. This in turn is parameterized in terms of the active volume of the crystal. At the time MGA was conceived it was envisioned as a safeguards tool to be used exclusively with LEGe detectors. The parameterization was therefore based on this assumption and the maximum detector volume that could be entered was 20 cm^3. In waste assay applications it is now routine to use large BEGe detectors for reasons of higher sensitivity. BEGe detectors have volumes up to about 150 cm^3. We have reviewed the database of BEGe detectors characterized at our facility to derive an appropriate parametric form for this class of large volume detector. The impact on MGA performance is considered.

Introduction and background

Plutonium is a special nuclear material that must be accurately measured and accounted for at all times and at all places within the nuclear fuel cycle. Non-invasive gamma-ray measurements of the isotopic composition are important in this regard because such measurements determine the fissile content of items without altering the items in any way. The relative abundance vector forms a unique attribute that can subsequently be used to identify it. Furthermore the results of isotopic analyses can be used to interpret other non-destructive data coming from, for example, neutron coincidence counters and calorimeters.

The Multiple Group Analysis code MGA [1-8] was developed to perform plutonium isotopic analysis on high-resolution gamma ray spectra gathered in-situ. Because of this the following defining characteristics are key to MGA:

- The code was designed to require no calibration apart from that of the energy scale. That is, the only data required by the code are fundamental constants (e.g. gamma-ray energies and branching intensities, half lives of the isotopes, and mass absorption coefficients that are written into the body of the code), the spectrum data and a file containing "setup" parameters.
- It was designed to attain the highest possible precision and accuracy in the shortest measurement and analysis time. This specification implies that the most intense peaks of the spectrum be used. By using the most intense, but also the most complex, regions in the spectrum in certain safeguards applications it requires only a few minutes of measurement time and can attain accuracies of better than 1%.
- It was developed to analyze a wide variety of samples usually without regard to: 1) physical form, size, shape, or container, 2) chemical form or elemental distribution, 3) actinide isotopic distribution (plus small amounts of other activities), and 4) the sample age. That is, both freshly processed and aged samples can be analyzed. The current version of MGA is capable of measuring the following actinides: all of the important isotopes of plutonium (except ^{242}Pu which is derived using a correlation technique), ^{241}Am, ^{235}U, ^{238}U, and ^{237}Np-^{233}Pa. Under certain circumstances, it can also measure the U/Pu ratio, detect the presence of ^{243}Am-^{239}Np and whether the ^{241}Am content is homogeneous, and measure (or determine the upper limits of) several long–lived fission products, when using the two-detector mode.
- The code was designed to operate with little or no user interaction. That is, all decisions regarding the treatment of the data must be made internally in the code based on the values of the spectrum data. MGA analyzes the data quickly and runs on conventional PC computers. It can be imbedded in, or linked to, other application codes. Within this minimal set-up environment MGA measures almost any size and type of plutonium sample. It can be applied to U/Pu ratio in MOX samples and can be used to measure the Pu concentration in solutions.

The evolutionary development of MGA began the early 1980's. Many capabilities have been added since that time as new needs, new measurement situations or new methods for analysis have become apparent. The dramatic increase in power and capabilities of computers has also greatly affected its development.

There is considerable interest in using MGA in association with the neutron coincidence method to measurements of plutonium in waste containers [2]. Since high accuracy (i.e. 1%) measurements are not usually required for this application, the isotopic values do not need be as good as for accountability type measurements. The principal gamma ray spectrometry problem that arises here is the very low number of counts obtained in spectra taken of low plutonium-content samples. Significant efforts have been devoted to "hardening" the code to analyzed statistically poor data, or exit properly so that unattended measurements may continue. Our experience indicates that a plutonium mass of 10 mg can be detected in a measurement time of 10-30 minutes in a 208 liter waste

drum filled with a low atomic number matrix (e.g. combustibles) of medium density (i.e. $0.3 g.cm^{-3}$).

Pu has a fairly soft gamma ray emission spectrum. The performance (detection limits – assay times) for the measurement of contact handleable waste items is therefore considerable improved if a large area detector is used so that the geometrical efficiency (solid angle) is increased. However when fission and activation products that emit high energy lines are also of interest it is also an advantage to have a thick detector to achieve a high stopping power. A similar need arises when the matrix attenuation is severe or when a high mass of Pu is present in a form that is highly self attenuating. In these cases the weak but more highly penetrating Pu lines may be used in the assay as a way of reducing the overall uncertainty. Differential peak analysis (plotting the apparent mass vs energy) forms the basis of a 'lump' correction strategy. Clearly therefore a wide energy range is a useful feature. A single detector covering both the low and high energy range effectively has a cost and complexity advantage since it requires only a single collimator housing and nucleonics chain. The challenge is to achieve the large volume detector and sought after aspect ratio with the energy resolution needed for analysis of the complex spectral regions used by MGA.

The Broad Energy Germanium (BEGe) detector configuration comprises a near right circular piece of high purity Ge typically with a large area flat face and a short length. This enhances the low energy efficiency and reduces high energy background in typical counting geometries. These detectors have thin (20-30μm) stable ion implanted front contacts so that the nominal energy range extends down to 3keV with appropriate low atomic number end-cap. This means that the efficiency is relatively easy to calculate using transport codes. Usually we choose to control the low energy response through the use of external filters as will become apparent later. The filters have the important role of limiting the dead-time rate loss particularly in those situations where the 59keV radiation from ^{241}Am is dominant. The BEGe is designed with an electrode structure that enhances low energy resolution and is fabricated from select Ge having an impurity profile that improves charge collection and thus resolution and charge collection at medium and high energies also. Consequently the resolution at low energies is equivalent to that of traditional Low Energy Ge (LEGe) planar detectors (widely used below 150keV) while at high energies it is comparable to that of good quality coaxial detectors. Additionally because of their larger volume compared to LEGe detectors they have high efficiency at medium to high energies (200-3000keV say). These are the features that make the BEGe geometry attractive for the measurement of the complex spectra from special nuclear materials and other gamma emitting radionuclides found in waste.

Basis of relative isotopic abundance analyses

Methods for determining isotopic abundance ratios by analyzing gamma-ray spectra are based on the following simple equation:

$$A/B = I_1/I_2 \cdot \varepsilon_2/\varepsilon_1 \cdot p_2/p_1 \cdot t_a/t_b \qquad (1)$$

where A/B is the ratio of isotopes A and B, I_1 and I_2 are measured gamma-ray intensities (net full energy peak areas) for peaks associated with these isotopes, ε_1 and ε_2 are the efficiencies for detecting the peaks, p_1 and p_2 are the gamma-ray emission probabilities, and t_a and t_b are the respective isotopic half-lives. The emission probabilities and isotope half-lives can be found in published reports [1] and can therefore be treated as constants. If the gamma-ray peaks are close in energy, the respective detection efficiencies become nearly the same, so that the ratio of efficiencies approaches unity. Therefore, only a "reasonably good" relative efficiency curve is required (i.e. only the shape as a function of energy and not the absolute scale).

The general equation used in MGA is actually formulated slightly differently from Eq. 1 because it must also include the shape of many peaks in addition to their integrated areas. Nonetheless, the principle expressed by Eq. 1 is retained. Since the emission probabilities and isotopic half-lives are fundamental constants, it is obvious from Eq. 1 that the important terms to be measured are the peak intensities and their relative detection efficiencies. However, these seemingly simple requirements are complicated by the following:

- There are not just two isotopes, but several isotopes whose relative abundance must be determined. For plutonium, the set of isotopes includes ^{238}Pu through ^{242}Pu and also ^{241}Am. Other isotopes must also be considered when present.
- Each isotope may exhibit from zero to several detectable peaks in a spectrum. Typically, only ^{242}Pu cannot be detected directly (except when its abundance exceeds 50%) and therefore must be estimated using an algorithm. When several peaks from a given isotope are available, all of the intense ones should be included in the analysis to obtain the most accurate results. In MGA, this is done by forming a matrix of equations, one for each data value that is used. The equations are linearized and after each equation is appropriately weighted by the variance of the data value, a least-squares method of analysis is used to determine the variables and their associated uncertainties.
- Many of the most intense peaks in a typical plutonium spectrum severely overlap each other. This is especially true in the 94 to 104 keV region of the spectrum that contains both gamma rays and x-rays. X-rays have a different peak shape than that of equivalent energy gamma rays. A special analysis method that includes the peak-shape character must be used to analyze such regions.
- A relative efficiency curve must be obtained that can be used to accurately determine the ratio $\varepsilon_2 / \varepsilon_1$. However, there are at least three main contributors to the shape of this curve; the detector, the sample, and the measurement setup (e.g. absorbers, collimators, sample containers, etc.) As a result, the number of variables that must be allowed in this determination is only slightly less than the number of peaks that are useful for defining the "intrinsic" efficiency curve. Furthermore, the curve is complicated by a discontinuity caused by the K-shell absorption edge of plutonium.

Fig. 1 illustrates some of the characteristics of the low- and high-energy regions of a typical plutonium spectrum.

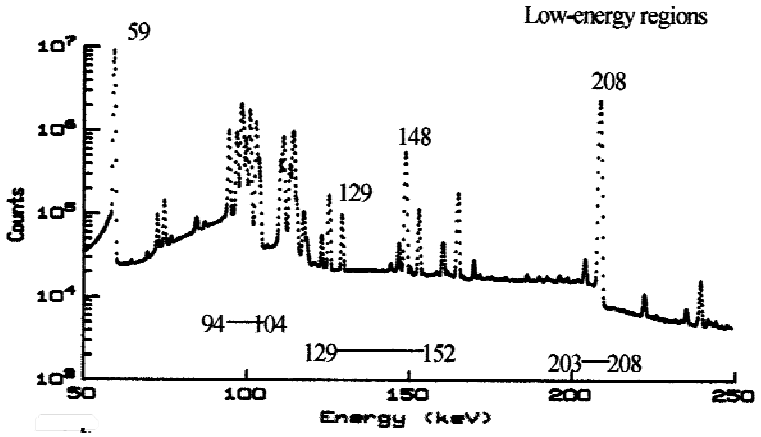

Fig 1. Typical low-energy spectrum of plutonium

The low-energy region contains gamma-ray peaks due to all of the isotopes of interest. Therefore, this region is generally used when viable. However, MGA is capable of also including the high-energy region, using either a second large detector or a single large volume detector that meets the energy resolution requirements for spectral deconvolution at the lower energies. The availability of both low– and high-energy analysis modes, under certain circumstances, improves and expands MGA's capabilities.

MGA uses the 94-104 keV region of the spectrum because, although the peak structure of this region is very complicated as Fig. 2 shows, this region nonetheless contains the most intense peaks of all of the plutonium isotopes and ^{241}Am (except for the region below 59 keV which is visible only when analyzing freshly processed samples). This point is particularly important when considering ^{238}Pu and ^{240}Pu which each emit only three low-energy gamma rays when they decay, the lowest being below 59 keV, the next in the 94-104 keV region, and the third ones are at 152 and 160 keV respectively. However, the emission probability of the three gamma rays diminishes greatly with increasing energy so that the 160 keV peak of ^{240}Pu becomes very difficult to measure and is therefore not included in the analysis process.

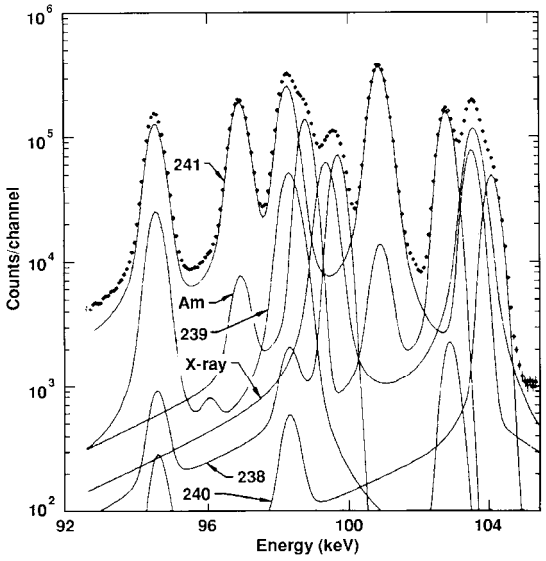

Fig. 2. 94-104 keV region of a plutonium spectrum

Based on these and other considerations the low energy mode of MGA typically extends to approximately 300keV (historically 4096 channels each 0.075 keV wide has been used as a standard setting). As discussed earlier however the energy range extends beyond this in high energy mode when the 414 keV peak from ^{239}Pu and others at even higher energy

(in the 770 keV region) carry critical information. Thus the requirement is to establish a relative efficiency profile from a few 10's keV to circa 800 keV or beyond.

Subroutine MGAABS

To determine the relative efficiency values needed in Eq. 1, it is necessary to determine an efficiency curve spanning the energy regions used in the analysis. This relative efficiency curve (often referred to as the "intrinsic" efficiency curve) cannot be determined by some prior calibration process but must be determined from the spectral data so that it properly reflects the conditions under which the data was acquired. Most other gamma-ray isotopic codes use a functional form for the efficiency curve that is not related to the physical processes involved in detecting the gamma and x-rays emitted by the sample. However, in MGA a functional form is used that closely approximates the three principal interactions involved in the detection process. To recap these are:

- The gamma-ray interactions with the detector (i.e. detector efficiency versus energy)
- Attenuation caused by absorbers such as Cd or other filters used to block low energy radiations and control the dead time losses
- Self-attenuation by the plutonium in the item

The following equation is used to describe these processes:

$$A_j = \left(\sum_{k=1}^{k=3or4} (p_{j,k} \cdot \mathbf{X_k})\right) \cdot \exp(-\mu_j \cdot \mathbf{CD}) \cdot (1 - \exp(-\mu_j \cdot \mathbf{PU}))/ \mu_j \cdot \mathbf{PU} \cdot \varepsilon_j^{\,o} (1-\mathbf{b} \cdot E_j - \mathbf{c} \cdot E_j^{\,2}) \quad (2)$$

where A_j are the areas of ten peaks in the low-energy region of each spectrum, due to ^{239}Pu, ^{241}Pu-^{237}U, and ^{241}Am and X_k are the unknown amounts of these isotopes. The absorption coefficients, μ_j, at each peak energy are known for Cd and Pu, but the thickness of the Cd filter and Pu sample thickness are usually treated as variables. The final term in Eq. 2 describes the detector efficiency as a function of the energy, E, where ε^o is approximate efficiency values for a Ge detector of volume *V* at energy E_j, calculated using the algorithm shown in Eq. 3, and the slope, b, and curvature, c, are treated as variables.

$$\varepsilon^o = \exp[S_{12} \cdot (\log(E) - 4.0605) + S_{13} \cdot ((\log(E))^2 - 21.207)] \quad (3)$$

where

$$S_{12} = 7.29 + .1205 \cdot V$$

$$S_{13} = -.93344 - .006553 \cdot V$$

and V is the active Ge volume in cm^3 (cm^3).

Eq. 2 is very non-linear in form and therefore the variables, shown in bold face type, must be solved by a method of iterative least-squares.

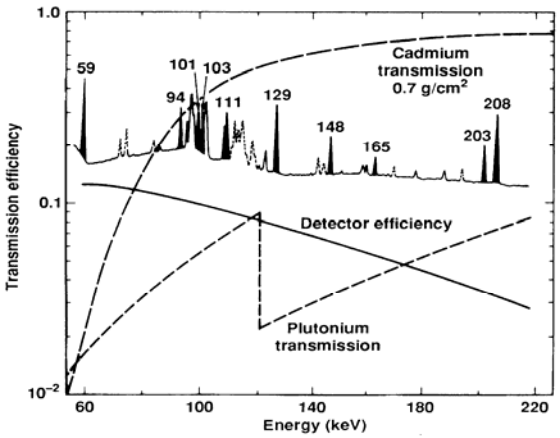

Fig. 3. Plot of three principle processes that characterize the "intrinsic" efficiency curve

The characteristics of the different components of Eq. 2 are illustrated in Fig. 3. The resulting curve for the total efficiency is used to determine the relative efficiency values required by Eq. 1

The intensity of ten peaks (determined in the subroutines MGAPKS and MGA94) are used in subroutine MGAABS to solve Eq. 2 for the variables involved. The peaks at 59, 94, 101, 103, 110, 129, 148, 165, 203, and 208 keV that are used are due to ^{239}Pu, ^{241}Pu, ^{237}U and ^{241}Am. Since ^{237}U is generally in equilibrium with its ^{241}Pu parent, the two components can then be treated as one, thus reducing the total number of variables to seven.

Because Eq. 2 is nonlinear, an iterative least-squares method is used that involves creating a linearized Taylor series expansion about trial values of the variables. The necessary photon branching probabilities and the Cd and Pu absorption coefficients are contained in data statements at the beginning of the subroutine listing. When the refinement matrix is solved for the variables, the answers represent incremental improvements to the previous estimates of the answers. A least-squares analysis is made after each update of the variables until the incremental answers are all sufficiently small, as determined by various convergence criteria. The detection efficiency can subsequently be determined from the following equation:

$$Eff_j = \exp(-\mu_j \cdot \mathbf{CD}) \cdot (1 - \exp(-\mu_j \cdot \mathbf{PU}))/ \mu_j \cdot \mathbf{PU} \cdot \varepsilon_j^{\,o} (1-\mathbf{b} \cdot E_j - \mathbf{c} \cdot E_j^2) \qquad (4)$$

Because the subroutine logic is very convoluted, containing numerous tests and boundary checks, it is difficult to predict or follow the path taken for any given analysis. The subroutine begins (for non-solution cases) with an initialization of parameters and analysis flags. This is important in this routine because proper convergence of the iterative process is quite dependent on good initial estimates and settings. These are determined from input or information gathered from the spectra up to this point, such as whether the sample is freshly processed or age, whether it contains uranium or not, and the statistical intensity of the data. Based on certain peak areas obtained thus far, a very crude estimate is also made of the relative abundance of the isotopes in the sample.

With these initial parameters, the code prepares matrix corresponding to ten peak areas (as expressed in Eq. 2) and seven variables that are to be determined. A standard least-squares calculation is to perform the analysis of the slightly over-determined set of equations. Following each calculation, the answers are subjected to a number of tests to determine their validity and uncertainty. The process usually employs “damping” of the incremental results, particularly if the increments are large, and checks to make sure they remain within predetermine boundary values (e.g. that the Cd absorption thickness can not be negative). Similar tests are made for the thickness of Pu in the sample and for the slope and curvature of the detector efficiency curve. If the convergence test fails during any of the tests, the convergence flag (ICNVRG) will not be zero and the analysis will be repeated. The process also includes removing the variables (i.e. holding them fixed) in a progressive manner.

Various tests are also made of the residual vector. They are made to determine whether the ^{237}U is in activity equilibrium with its ^{241}Pu parent and whether the sample contains uranium or not. Samples containing low enriched uranium cannot always be detected in subroutine MGA235, but can sometimes be detected in this subroutine by an excess intensity of U x-rays. Whenever either of these conditions is detected, appropriate flags are set and the entire MGA analysis process is restarted.

After all tests and conditions have been met, the routine computes and stores the analysis results for use in later routines. These results include the approximate relative activity levels of the isotopes, the Cd filter thickness, the Pu sample thickness and two variables used to describe deviations from the calculated generic efficiency curve for a detector of volume *V*.

Review of the BEGe data base

BEGe detectors are manufactured with cross-sectional areas from 2000 to 5000mm^3 and thickness' of 20 to 30mm (contrast this with LEGe detector which have corresponding ranges of 50 to 3800mm^3 and 5 to 25mm respectively). They are generally made in a few standard configurations with controlled dimensions so that within a model number they are practically interchangeable for isotopics and certain other measurements without gross changes in response. For low energy counting applications low background composite carbon windows are normally fitted although Be is also available. For waste assay attenuation in the waste matrix and container walls means that there is no requirement to retain the highest efficiency below 45 keV, say, and so Al is normally the window material of choice. Table 1 summarizes the salient features of the standard range of BEGe detectors currently most widely deployed. The designation BEaatt denotes a nominal area of aa multiples of 100mm^2 and a thickness of tt mm.

A large number of BEGe detectors have been manufactured at our facility. Many of these have undergone an extensive characterization process prior to delivery to support mathematical modeling of the response in diverse conditions. This has resulted in an extensive database of efficiency information gathered under standard conditions that can be mined to answer questions such as how to parameterize the efficiency curve.

Model	A (mm^2)	t (mm)	ε_{rel} (%)	R(122keV) (eV)	R(1332keV) (eV)	$D_{crystal}$ (mm)	$D_{end\text{-}cap}$ (mm)	V (cm^3)
BE2020	2000	20	9	<650	<2000	50.5	76	40
BE2820	2800	20	13	<700	<2000	57.7	82	56
BE2825	2800	25	19	<700	<2000	59.7	82	70
BE3820	3800	20	21	<700	<2100	69.6	89	76
BE3825	3800	25	28	<750	<2100	69.6	89	95
BE3830	3800	30	34	<750	<2100	69.6	89	114
BE5020	5000	20	28	<750	<2100	79.8	102	100
BE5025	5000	25	37	<750	<2200	79.8	102	125
BE5030	5000	30	50	<750	<2200	79.8	102	150

Table 1. Summary of standard BEGe configurations. Listed for each model number are the crystal area, thickness, nominal full energy peak efficiency for a point source at 250mm at 1332keV relative to a standard 3"x3" NaI(Tl), full width half maximum resolution at 122keV and 1332keV, crystal diameter, nominal end-cap diameter and nominal crystal volume including inactive regions (or dead layers).

This database of measured detector efficiency calibrations was searched and a representative sampling of 17 detectors was selected to provide data over the full range of detector volumes. This empirical efficiency calibration data (without Cd absorber or Pu self-attenuation) was then used to evaluate the quality of the efficiency parameterization. Leaving the Cd absorption and Pu self-attenuation terms off, coefficient values were selected according to the following updated code:

```
-----------------------------------------------------------------
C   Check input detector volume
 if (detvol .lt. 5) detvol = 5. !Lower bound
 detv = detvol
 if (detv .gt. 20.) detv = 20. !Upper bound
 shapc(1) = .03 + .008*detv  !Estimate system noise
 shapc(2) = .0017 + .000018*detv !Estimate FWHM slope
 a1 = 7.29     !Coefficients for < 15 cc det.
 a2 = .1205
 b1 = -0.93344
 b2 = -0.006553
 if (detvol .gt. 15) then
   if (detvol .lt. 40) then
     a1 = 9.228    !Coefs. for det 15<vol<40 cc
     a2 = -0.1152
     b1 = -1.0514
     b2 = 0.01276
   else
     if (detvol .gt. 150) detvol = 150 !Maximum det. vol.
     a1 = 4.788    !Coefs. for det 40<vol<150 cc
     a2 = -0.0042
     b1 = -0.56854
     b2 = 0.000688
   endif
 endif
 shapc(12) = a1 + a2*detvol  !Estimate efficiency slope
 shapc(13) = b1 + b2*detvol  !Estimate efficiency curvature
C
 return
-----------------------------------------------------------------
```

The **b** and **c** coefficients of Eq. 4 were then optimized to provide the best least squares fit of the equation to the measured data. The two smallest detectors (8 and 14 cc) maintained the same coefficient values as before the update, as shown in Figure 4. Two larger detectors (70 and 154 cc) can be seen to have greatly improved the quality of the model to the fit, as shown in Figure 5. All of these relative intrinsic efficiency plots have been normalized to data points at 122 keV for consistent comparison. Figure 6 shows a summary of all 17 detectors, with the figure of merit measured as the χ^2 of the fit in each case. Data used in the fit: 45.1, 59.6, 122, 245 and 344 keV. Other calibration data points at: 779, 964, 1112, 1408, 2000, 3000, 5000 and 10000keV. Data from ISOCS characterization measurements is supplemented by MCNP™ modeling.

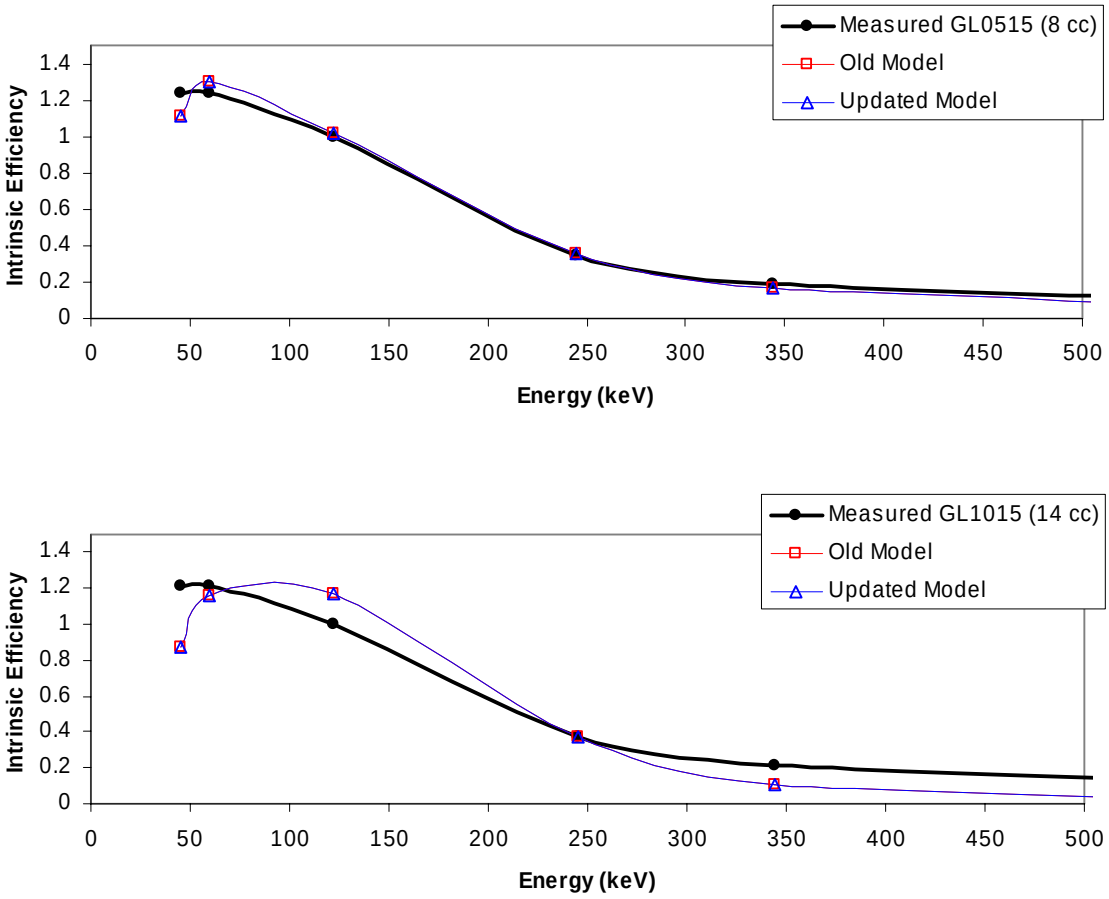

Figure 4 – The quality of the efficiency model to the measured data for two small detectors. The old and new efficiency models were the same for these cases.

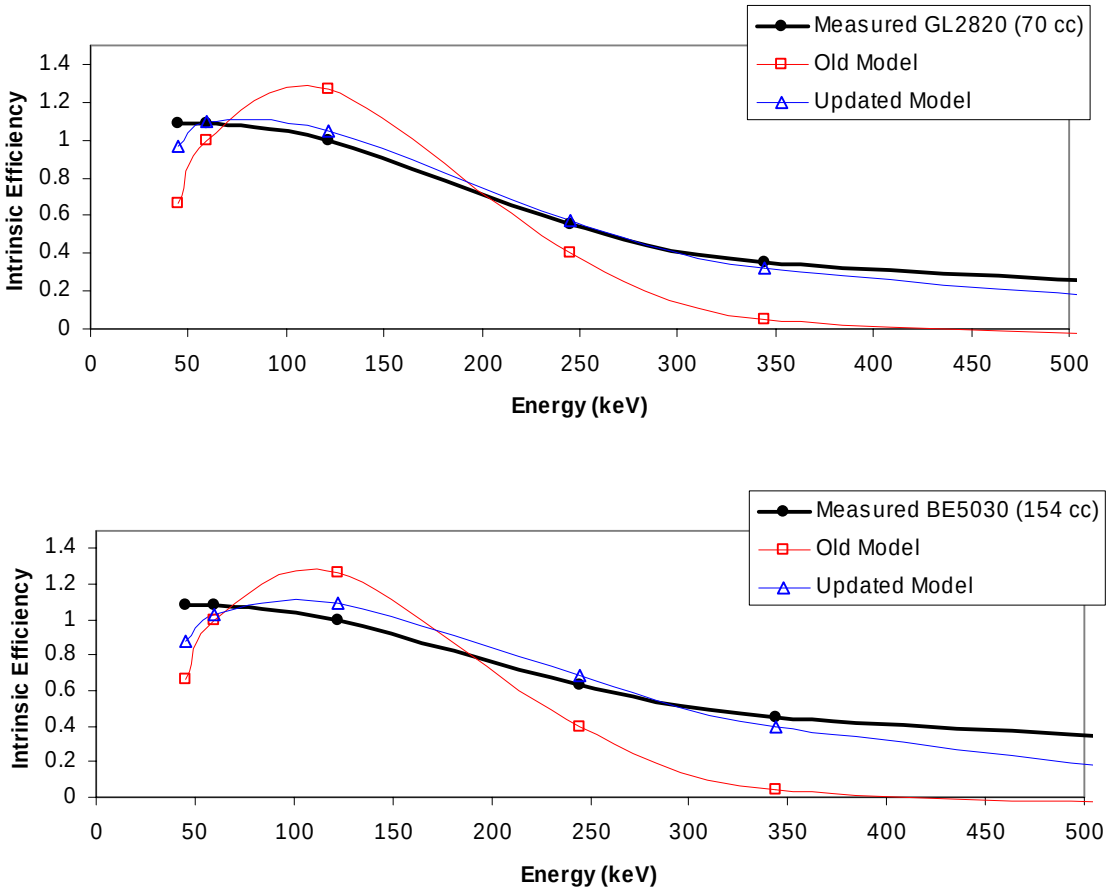

Figure 5 – The quality of the efficiency model to the measured data for two large detectors. The update improves the model.

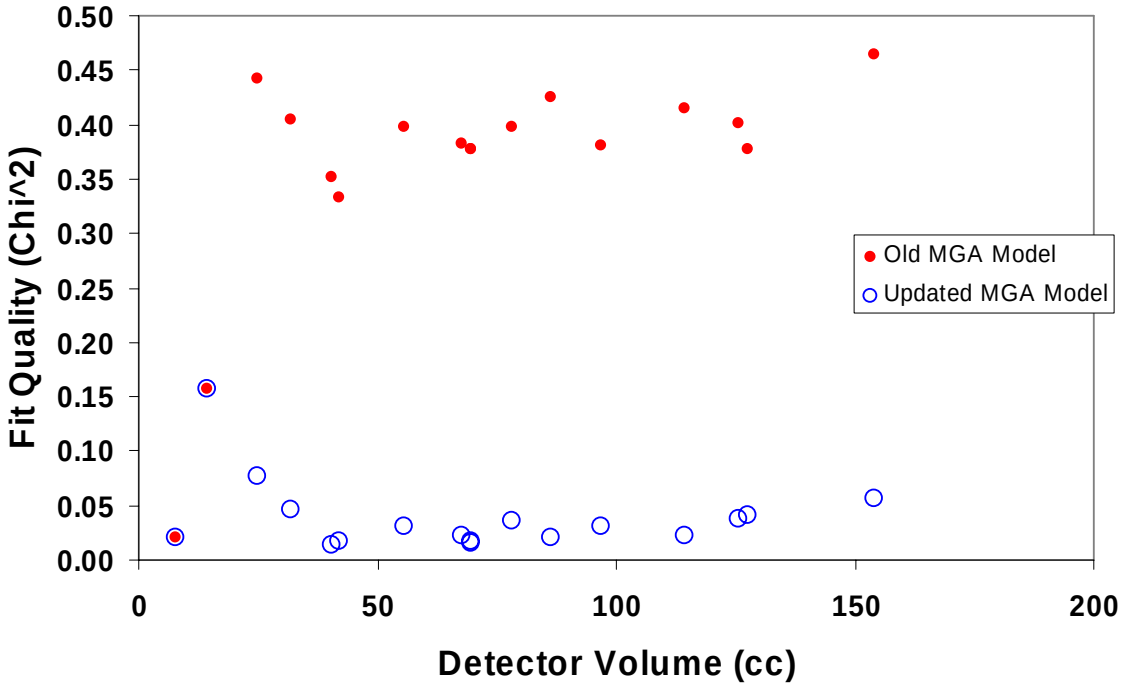

Figure 6 – Summary of all 17 detectors showing the quality of fit for the models to measured data. The update consistently improved the results.

Discussion

To achieve the level of operational simplicity and robustness provided by MGA sophisticated algorithms are include in the code. One of these involves deriving the relative detection efficiency of the Ge spectrometer used to gather the data. In this work we have examined the impact of detector volume on the parameterization of this function. In particular we have developed a new scaling rule specifically for the case of BEGe detectors.

MGA was developed a number of years ago primarily for safeguards applications. It analyzes the complex 100keV region of the spectrum so that good energy resolution is needed. At the time the detector of choice was the LEGe configuration. Some of the internal routines are based on the assumption that a small volume LEGe will be used. A LEGe volume parameter is used by MGA. In general terms it is used to scale the efficiency (and the resolution) and is especially important when the quality of the spectrum is poor.

For waste assay the accuracy of the isotopics determination can be relaxed to some degree and the optimum detector is often one that covers a broader energy range with higher efficiency. This means selecting larger detectors with large area to length aspect ratios and sacrificing, to some degree, resolution. The BEGe detector has proven to be a good compromise giving sufficient resolution at low energies for reliable application of MGA while having an adequate efficiency at the higher energies of interest for assaying special nuclear materials, fission products and activation products.

The (original) upper limit for the detector volume parameter in MGA is $20cm^3$ (which is tiny by the standards of modern HPGe detectors typically now used in waste assay). Because of this limitation and confusion over how to select the appropriate detector volume in such cases we have several systems running on a default setting of 15 cm^3, we also have systems running with true volumes [e.g. LEGe detector volume set to 76.97 cm^3 (35mm detector radius, 20mm detector height)].

For large HPGe detectors of the type routinely used in waste assay we recommend a set-up value of 20 cm^3. Provided the spectra are 'good' it makes no difference and if a value greater than 20 cm^3 is used the scaling parameters for the 'nominal LEGe' get clamped internally anyway by MGA to the case of the 20 cm^3 detector volume. For waste applications the statistical quality of the spectra, especially close to the detection limit and/or for heavy dense items are quite often pooer and the spectra more cluttered.

The reason for this recommendation is because the volume parameter value is used only to get an approximate slope and curvature of the efficiency curve up to about 208 keV. This shape does not change significantly - for the present purposes - after you get to a volume of 20 cm^3. Using a correct detector volume parameter allows the MGA code to determine reasonable good efficiency slope and curvature values for the iterative least-squares process – i.e. it makes a better first trial estimate. But the input values are important *primarily* when the peak intensities are low. In this case, the code has a very difficult time converging during the iteration process of solving the set of equations used to determine the parameters affecting the efficiency curve. In this case, the code will resort to using the detector efficiency curve based on the volume parameter and allow the iteration process to only determine the Cd absorber and Pu sample surface densities. There is a possibility therefore for the performance not to be smooth with statistics but to step-change at some tilt point.

Setting this fine detail aside it should be clear therefore that for routine operation using the existing MGA modules there should be no performance difference between typically used detector volume parameters for waste assay (15 cm^3 and above). This explains why empirically we find that MGA performs well in practice for a wide range of detector types and sides (LEGe, BEGe and coaxial).

In this paper we have examined how best to parameterize the efficiency of BEGe detectors in terms of the crystal's dimensions. The BEGe configuration is essentially equivalent to a large LEGe. Therefore we have extended the parameterization to large planar detector volumes explicitly. In future releases of the MGA software we hope to

remove the 20cm^3 volume limit so that actual values can be used making the system set up self consistent.

Conclusions

This paper is part of the continuous review of the algorithms embedded within the MGA computer code to ensure that it reliably meets the changing measurement challenges placed before it. The Multiple Group Analysis (MGA) code has been modified to better accommodate the larger volume detectors now available for plutonium isotopic measurements. This paper verifies the adequacy of the changes and empirically validates the detector efficiency parameterization. The Multiple Group Analysis (MGA) code can now be explicitly used with Ge detectors with volumes larger than 20 cm^3. The appropriateness of the efficiency parameterization is demonstrated. The revised efficiency model is consistent with the old model for small volume detectors (5 to 20 cm^3) and is a significant improvement for larger volume detectors (e.g. up to 150cm^3).

References

1. An extensive but far from exhaustive listing of relevant references can be found in the following two reports:
   a. R. Gunnink, *MGA: A Gamma-Ray Spectrum Analysis Code for Determining Plutonium Isotopic Abundances*, Volume I, Lawrence Livermore National Laboratory, Livermore, CA., UCRL-LR-103220, (1990)
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