Proficiency Test in the Analysis of Gamma Spectra for Malevolent Radiological Situations (MALRAD)

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Abstract

The MALRAD activity was intended to provide an exercise activity with respect to gamma ray spectrometric response to malevolent situations involving radioactive sources. Such situations can often be characterised by high activity sources in difficult contexts where the response is by necessity conducted with less than optimal instrumentation. Seven scenarios were developed based on previous incidents where possible and gamma spectral data and other information was disseminated to participants who were given one week to respond to each scenario with as much information as possible. In total 14 individual laboratories responded. The majority of laboratories were in a position to satisfactorily identify sources where single sources were used in situations with no complicating factors. For those scenarios involving heavy shielding som difficulties were encountered due to distortion of the spectrum from that which would normally be viewed as characteristic for the isotope in question. Special nuclear materials such as reprocessed enriched uranium and weapons grade plutonium provided different challenges and there were indications in the reponses from participants of unfamiliarity with these materials.

Key words

Gamma ray spectrometry, special nuclear materials, sources

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1. Introduction

Recent years have seen a widening of the range of contexts within which radioactive materials may be encountered and a concomitant widening with respect to the types of instrumentation being deployed and the kinds of agencies being equipped with such instruments to counter radiological malevolent acts. Whether or not the risk of malevolent use of radioactive materials has actually heightened over the past decade is a subject of debate but what is more certain is that the perception of the risk is higher in certain sectors and has resulted in a wider range of instruments being marketed by a greater number of manufacturers and being aimed at a more diverse market. Many of these instruments have spectral acquisition capabilities and include various functions for the identification of sources. Whereas twenty years ago first response personnel may have had access to, at most, simple dose meters, in the current climate a range of responders may have access to relatively advanced instrumentation with features more akin to those found in laboratory based spectrometers. The rate of this expansion in terms of the types of equipment available, the potential situations where it may be employed and by whom may be argued to constitute a potential weakness with respect to the fact that training of responders in the use of the equipment with which they are being provided may not be a priority in all cases. Pressures from various directions often mean that the priority is that the responders are seen to be equipped with little attention focused on the efficacy with which they can employ the equipment. Such situations engender two requirements: the first being naturally enough a focus on training of personnel with respect to the equipment they are expected to use and the second being the ability of organisations or institutes to provide expert opinion or support with respect to information gathered by such first responders. In this context, communication links between responders and centralized locations where necessary expertise may be located are becoming the norm. In addition to the above, malevolent situations may expose laboratories to sources and materials which would not normally be a part of their usual operations. In this context, special nuclear materials (SNM) are a significant challenge. Although the interdiction of such materials will ultimately involve international organisations and the expertise they can bring to bear, individual countries must be in a position to conduct a preilimary analysis of such materials to fulfill both their own requirements in terms of response and to be able to make informed decisions prior to actually involving external agencies.

The MALRAD exercise was intended to address a number of aspects in relation to the topics mentioned above. It was hoped that the exercise would provide a situation whereby

participants could practice the analysis of data generated (by themselves or an external team) in response to the use or potential use of radiological materials in a malevolent context. The nature of such data is different in many ways to that generated in the laboratory on a day to day basis and the only way to ensure that organizations/analysts can operate effectively with such data is by practice. The equipment with which such data is generated is often such that the spectra generated are of lower quality than spectra obtained in the lab and necessitate different approaches with respect to analysis. The sources involved in malevolent acts may potentially be isotopes with which many analysts are unfamiliar and may be present at activities that complicate their identification from gamma spectral information. The contexts in which they occur can also be significantly different to laboratory situations and factors such as shielding, scattering and distance can all impinge on the analysts ability to correctly identify the isotope in question. Where the data has been accrued by non-expert personnel in the field, the way in which the spectrum has been obtained may be less than optimal. The spectrum may have been counted for too short a period or using a detector type not particularly suited for the task to hand. Such factors can impose additional difficulties in using the data to generate as much information about the source as possible. Malevolent acts may also involve isotopes or mixtures of isotopes that result in analytical signals of such complexity that even the use of quality equipment under laboratory conditions is not enough to simplify the matter and in cases such as these, the experience of the analyst is paramount in performing a correct quantification or identification.

A number of exercises have been held in recent years in the Nordic countries involving the measurement of radioactive sources (primarily within the context of "orphan" sources) in the field using typical first response instruments. These have included the activities LIVEX and DEMOEX held within the context of Barents Rescue. Although such exercises are invaluable in providing much needed exercise opportunities in the field, the unavoidable logistics and practicalities confer some limitations. These are primarily in relation to the range of isotopes being used and the activities present. With respect to the suite of isotopes in use, such exercise are typically limited to the sources available within the country – medical, industrial and calibration sources of isotopes such as ^{137}Cs, ^{241}Am, ^{60}Co, ^{192}Ir etc. These of course may not be fully representative of the suite of isotopes available for malevolent purposes which may be sourced outside the country. In addition, a number of sources exist for which exercising in the field is all but impossible. The activity of isotopes that may be employed in malevolent

situations may also be significantly different to the activities of sources that are amenable to the organization and conducting of field exercises.

1.1 Aspects of the Scenarios

The MALRAD exercise was focused on addressing the aspects of response to malevolent situations involving radiological materials that may be difficult or impossible in the field or in reality or that present special analytical challenges. The exercise was intended to present situations involving contexts, isotopes, activities and instruments of relevance in first reponse situations or malevolent scenarios and which would provide an interesting analytical exercise for as many of the participants as possible. The majority of the MALRAD scenarios involved typical acts of a malicious nature – bombs, intentionally harmful exposures to actual sources, spreading of radioactivity without the intent to harm but to make a point or protest and sources being involved perhaps unintentionally in criminal acts. Two of the scenarios involved the use or smuggling of SNM. Most of the scenarios and the sources featured were based either wholly or in part upon scenarios that have occurred earlier and have been documented to greater or lesser extent. The bomb scenario has of course not occurred in actuality so in this case a real terrorist bomb from earlier was used in combination with a plausible source. The smuggling scenarios and sources were based closely on real life events involving SNM which have been reported earlier. Whilst these are not strictly first response scenarios, it can be argued that a state should be in a position to at least conduct a preliminary analysis of sources consisting of SNM and previous incidents have shown that this will typically be by gamma spectrometry in the first stages. One scenario involved the use of radioactive material in a protest action. While it is unknown if this has occurred previously, the willingness of militant groups (be they environmental, animal rights, etc) to engage in such actions with other materials (toxic wastes, animal blood, refuse, etc. related to the cause being protested), the documented use of the particular material involved in the MALRAD scenario in other situations (primarily the harming of an individual using this specific material) and the fact that such intermediate or low level materials are perhaps more easily obtained than high activity materials (or perceived as more easily obtained), engenders a certain plausibility to the scenario and it was therefore included.

All the sources involved could realistically be expected to feature in malevolent acts either by virtue of their usefulness in weapons (such as enriched uranium or plutonium), their accessibility (medical isotopes, low level materials) or their activity (highly active industrial

sources). The detectors involved in MALRAD consisted of the usual first reponse instruments based on sodium iodide systems of different sizes and in two instances HPGe detectors. The newer CdZnTe type was featured as new instruments coming on the market tend to feature detectors of intermediate resolution between HPGe and NaI – such as lanthanum halide type detectors. These latter detectors were not included as it was felt that CdZnTe is more "intermediate" in terms of resolution than lanthanum halides and would therefore be more of challenge, it eliminated the technical challenge of accurately constructing the relatively complex background of such detectors due to contaminant activity and it introduced an element of unfamiliarity in that CdZnTe detectors are usually employed over a limited energy range. CdZnTe detectors also tend to feature prominently in the the more compact "radioisotope identifier" types of instrument marketed to first response agencies. Full and complete information about detectors employed for each scenario are included in the descriptions of each scenario.

1.2 Scenario Information

For each scenario, sources and activities employed were based on typical industrial/medical sources in common use, amounts of material that have been involved in previous incidents or estimates of amounts that could be considered reasonable within the context of the presented scenarios. Information as to nuclear data (energies, probabilities etc) were retrieved from the online Table of Isotopes hosted on the website at Swedens Lund University (http://nucleardata.nuclear.lu.se/nucleardata/toi/welcome.stm) as it was assumed that this was reasonably accessible to most participants. Dose calculations were conducted using MicroShine® and MicroShield® from Grove Software Inc. as well as RadPro (McGinnis, 2008). Calculations of ingrowth and decay were based upon the US DOE's Radiological Toolbox (Eckerman and Sjoreen, 2006). Spectra were simulated according to the codes of Hensley et al (2005) and Plenteda (2002), via manual modification of actual spectra or by the addition of actual and synthetic spectra. Spectral conversions were conducted using either home made routines or SPECON 2000 (Hong, 2001). An arbitrary discrimination level of 30 keV was applied to most scenarios as this was deemed realistic for the detectors concerned and avoided unnecessary calculations at the lower energy end of the spectra. Although scattering is a problem in making gamma measurements of the type represented in some of the MALRAD scenarios, simulation is a problem due to extreme calculation times. In an attempt to avoid this, detectors were "collimated" although in one case an attempt was made to include a scattering contribution by recording an actual spectrum and then removing the

gamma photopeaks from it. The synthetic spectrum was then superimposed on the scatter contribution and the two spectra merged. Backgrounds were not added in most cases as it was felt that the contribution of background in most cases given coun ttimes and activities would have been minimal. Where they were added, real background spectra were added to the simulated spectrum. Effects due to beta and neutrons (including activation products in shielding materials) were not included in the simulation for convenience purposes. The MALRAD activity itself was conducted in two phases – the first being distribution of a practice scenario and the second being the distribution of the 7 exercise scenarios.

1.3 Practice Scenario

Approximately two weeks before the activity proper, a practice scenario in the exact same format as the test scenarios was sent to participants. This consisted of a trivial case utilizing a point source NaI spectrum of 1 MBq of ^{226}Ra + daughters. The main purpose of this scenario was to test procedures and ensure that all participants could handle the material with their systems.

2. The Scenarios

The following section provides an overview and technical details as to the 7 MALRAD scenarios. Indepth spectral details may be found in the relevant appendices. Suggested solutions to the Scenarios are provided only as examples using minimal software resources and time and are not intended as "model" or correct solutions .

2.1 Scenario 1

The objective of scenario 1 was the simulation of data generated in response to a hypothetical radiological dispersion device (RDD). Although there are essentially no documented examples of such an event, the potential consequences and the attention they receive warranted its inclusion. The source for scenario 1 was assumed to have been an RDD employing a 370 GBq (10 Ci) ^{241}Am/Be well logger that was 10 years old. Based on an initial activity of 370 GBq and an age of 10 years, the activities of the source and its daughters were calculated to be as displayed in Table I.

Isotope	Initial activity (GBq)	Activity after 10 years (GBq)
Am-241	370	3.64117E+02
Np-237	0	1.18881E-03
Pa-233	0	1.17623E-03
U-233	0	2.55966E-08
Th-229	0	7.98090E-12
Ra-225	0	7.84030E-12
Ac-225	0	7.74780E-12
Fr-221	0	7.74780E-12
At-217	0	7.74780E-12
Bi-213	0	7.74780E-12
Po-213	0	7.58130E-12
Tl-209	0	1.67351E-13
Pb-209	0	7.74780E-12

Table I. Decay of parent and ingrowth of daughters over 10 years for Scenario 1. Shaded isotopes are those included in the simulation.

Given that inappreciable amounts of daughters would be present below ^{233}U for the time period, the simulation was only conducted for this isotope and the preceding parents. For the purpose of the exercise, it was assumed that the logger had been dismantled entirely and the source had been fully exposed and was present in a dispersible form of small volume. The distance between the detector and the source and the small size of the latter facilitated its handling as an effective point source. The bomb type chosen for the scenario was that of the London Docklands bombing of 1996 given that it was large and details are available. The source was assumed to have been placed centrally within a mass of 500 kg of a standard ammonium fertilizer/fuel oil blasting mixture (ANFO) as is typically found in homemade explosives or as is purloined from quarries etc. For the shielding calculations the mixture was assumed to primarily have the chemical composition NH_4NO_3 (5% H, 35% N , 60% O w/w nominal) which has a density of 1.725 g/cm^3 but a density of 0.84 g/cm^3 when mixed with the appropriate amount of fuel oil. This matrix was in a container of volume 0.595 m^3 in the geometric form of a cube of side length 84 cm which was assumed to have a negligble contribution to shielding (paper or cardboard). This was then further assumed to have been covered in a lead sheet (standard “lead blanket”) of uniform thickness 2 mm and placed centrally in the back of a truck whose construction on the side for measurement was to be 1 mm of iron. The width of the truck was 2 m and the detector was then positioned normal and central to one side of the cube and at a distance of 1.0 m from the source itself, in effect up against the side of the truck. The problem reduced to that of a point source with shielding

between it and the detector. The effective shielding was that of 2 mm lead plus 1 mm of iron in addition to the shielding provided by 43 cm of the hydrogen rich explosive. Self attenuation within the "point" source itself was neglected. The neutrons that may have been expected to emanate from the well logger were not simulated although it is plausible that such neutrons would not have been detectable outside of the truck given the hydrogen rich nature of the bomb materials. On the other hand it is also plausible that there would be some induced activity due to the neutrons which would have resulted in a gamma signal but this was neglected based on the assumption that that activity would have been negligible relative to the source activity.

Two dose measurements were provided, one calculated for the same position at which the spectrum was taken and the second measurement one meter further back along the same axis. The background dose in the area was stated as 0.11 μSv/hr. The dose rate at position one (side of the truck) was stated as being 0.5 μSv/hr and at position 2 (1 m away from the side of the truck) 0.21 μSv/hr.

The simulated detector was a standard 3 x 3 inch NaI detector with an aluminium frontcap of 0.5 mm thickness being 4 mm from the crystal face. The nominal resolution was 6.9% at 662 keV. The spectrum was counted over 1024 channels covering the energy range 10 to 2600 keV. The count was for a live time of 600 seconds. The participants were informed that the detector was collimated such that scattering effects could be expected to be lessened with respect to the spectrum. Random statistical noise was added to the spectrum after simulation. A simulated background signal was also added to the spectrum, the primary effect of this being the appearance of a slight ^{40}K peak at 1460 keV. A point source spectrum was also provided as a means of calibrating for shape and energy. This consisted of a weak source (less than 1 kBq each) of ^{241}Am, ^{109}Cd, ^{137}Cs, ^{60}Co and ^{88}Y held at 10 cm from the detector face and accrued for a period sufficient to give good statistics. For follow up, the participants were provided with the above two spectra on an 8k HPGe detector over the same energy range counted for the same time and in the presence of the same absorbers.

The primary potential problems with the spectrum as provided were the activity of the source and the thick shielding between source and detector. Although ^{241}Am has a range of gamma rays, the vast majority of commercially provided libraries include just the one primary line at 59.5 keV although some specialised libraries within such packages outline the full suite.

Normally this low energy line will dominate the spectrum of ^{241}Am but in this situation, the shielding present served to reduce the significance of this line in the spectrum and allow other normally less significant lines to dominate (see Figure 1). In particular, ^{241}Am possesses a range of weak lines in the 200 to 400 keV and the 600 to 800 keV region, one of which has the potential for being easily mistaken for the 661 keV line of ^{137}Cs. In a "normal" situation the spectrum would be even more difficult due to scattered radiation and the presence of a collimated detector was used in the scenario to attempt to "remove" this complication. In real circumstances without collimation it is most probable that the small 59.5 keV peak would not be evident at all or only found with difficulty due to a much higher low energy signal from scattering. The identification of the spectrum as ^{241}Am would obviously depend upon the analysts/softwares ability to locate the 59.5 keV line. Perhaps the worst case situation in this scenario would be failure to identify the ^{241}Am source with misidentification of the source as ^{137}Cs or some other isotope. Alternatively a situation could be envisaged whereby ^{241}Am was identified and where a number of potential false positives would also be deemed present.

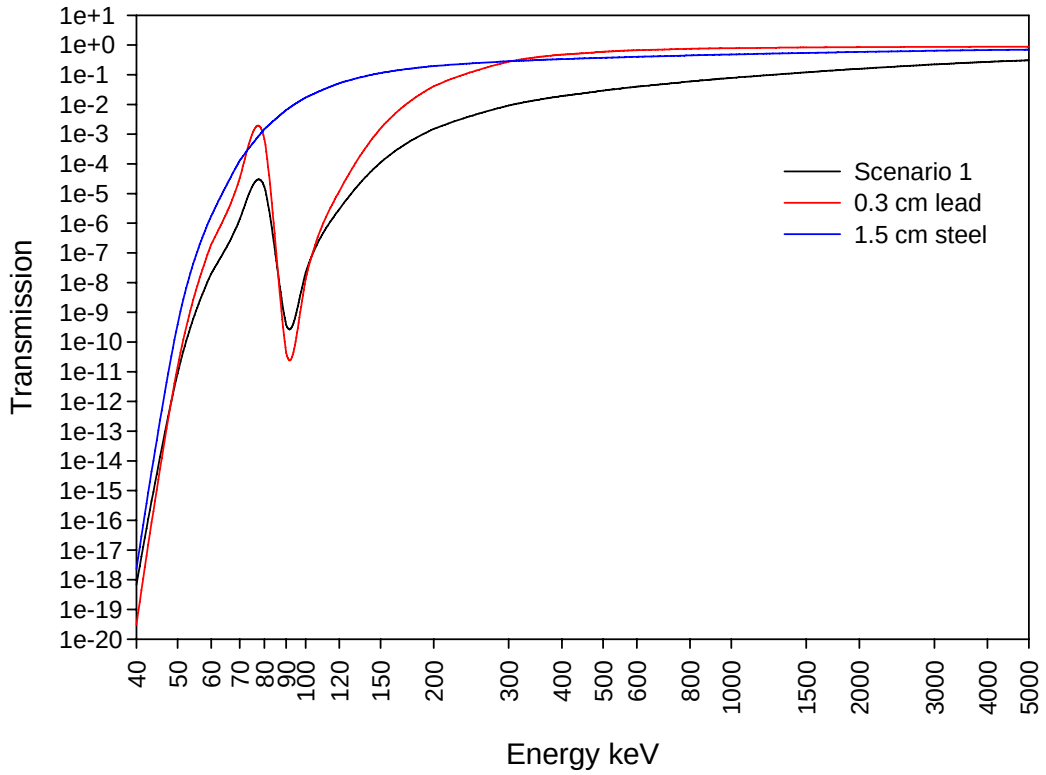


Figure 1. Graph of calculated transmission against photon energy for Scenario 1 and the two participant shielding estimates.

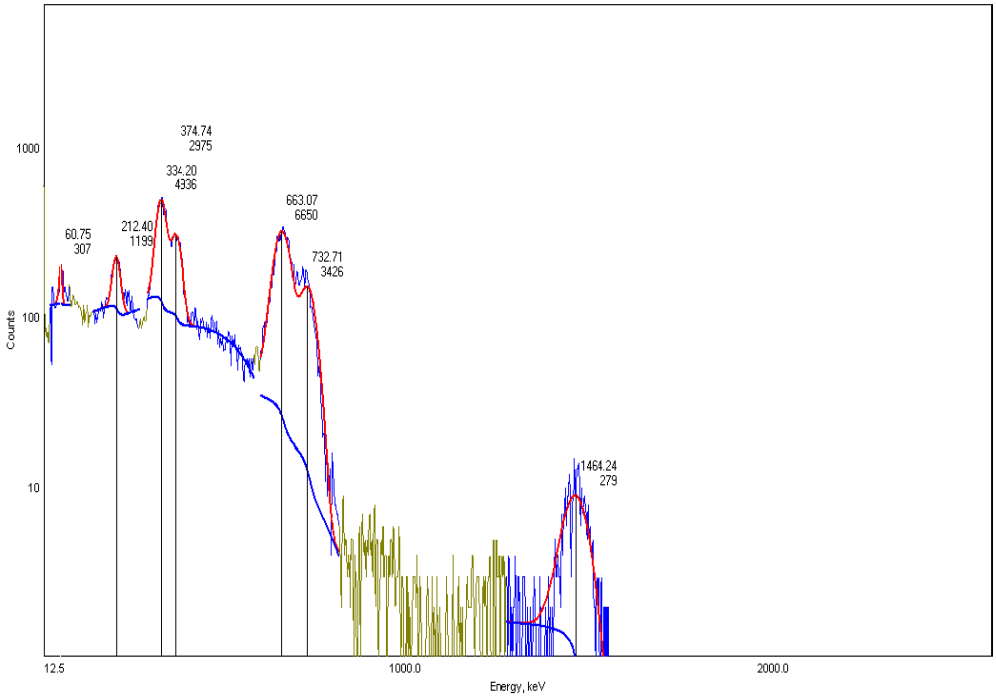


Figure 2. Correct location and identification of major constituent peaks in the spectrum of Scenario 1 using commercial software.

The dose data provided consisted of the results of two measurements, the first being at the point where the spectrum was taken and the second 1 m back. The corrected dose rates for these two positions were 0.39 and 0.1 µSv/hr. Using the relationships:

$$r_1 = \sqrt{\frac{D_2 \cdot r_2^2}{D_1}} \qquad A = \frac{D \times r_1^2}{\Gamma}$$

where

A = source activity in GBq

D = background corrected doserate measured at distance r_1 from source

r_1 = distance in meters to source

Γ = Gammaconstant (mSv/h) pr GBq at 1 m distance for the isotope.

would provide a measure of the distance between the first measurement point and the source of approximately 0.5 m and two activity estimates of 1.3 GBq and 3.0 GBq both estimates being significantly lower than the reality due to the shielding present.

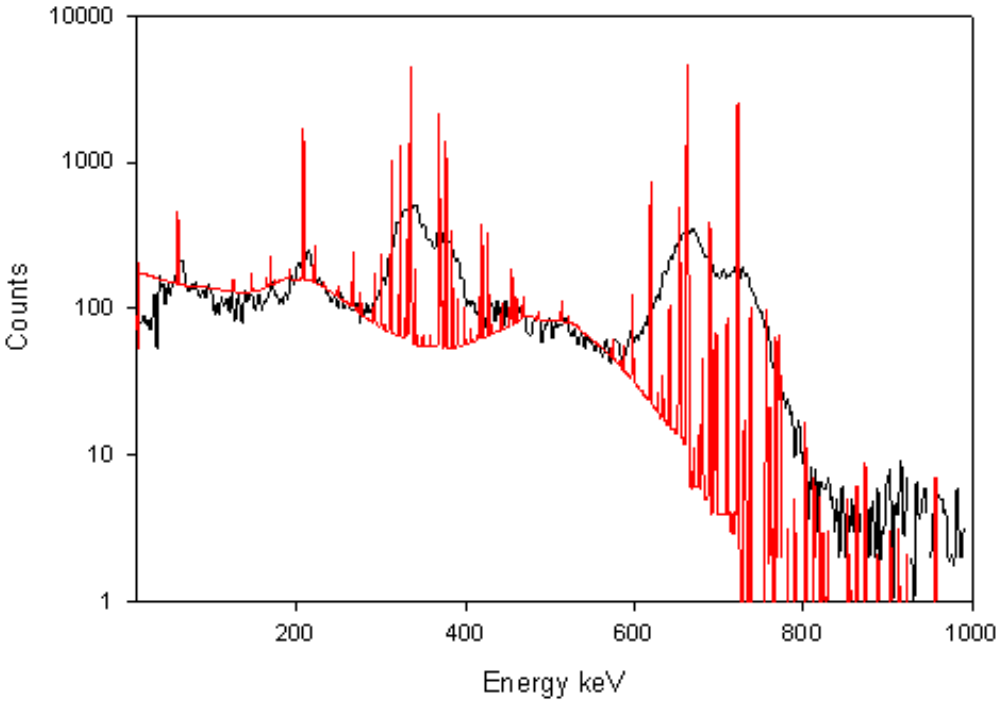


Figure 3. Comparison of the spectral region between 10 and 1000 keV for NaI (black line) and HPGe (red line) for the ^{241}Am source of Scenario 1 (spectra adjusted vertically for comparison purposes).

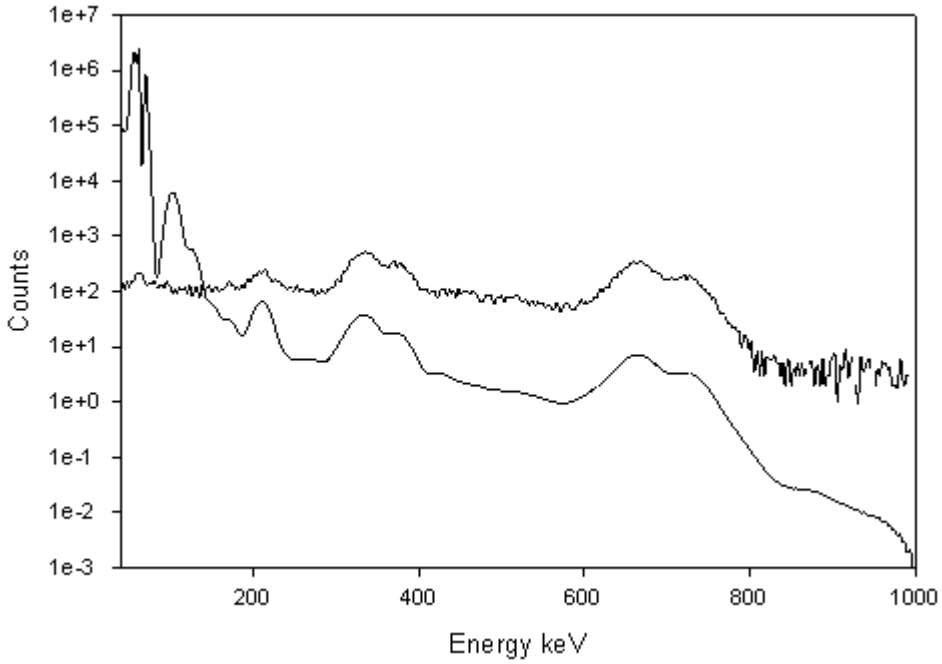


Figure 4. Comparison of NaI spectra for the unshielded ^{241}Am source and the shielded source under the same conditions. Note that the 59 keV peak is truncated in the unshielded spectrum due to an overflow in the simulation.

2.1.1. Reported Results

Participant	Reported Data
1	Source not clearly identified from spectrum. However, ^{239}Pu could be a possible candidate. ^{239}Pu amount estimated from dose rate measurements at 50 MBq or 0.02 g.
2	Participant withdrew
3	Participant withdrew
4	^{241}Am (small peak at 60 keV, probably due to shielding of side of car) and possibly ^{152}Eu, ^{239}Pu, ^{137}Cs and ^{40}K (background)
5	Unidentified source
6	No data reported
7	The source is not identified. There is no data in available database on radionuclides with the gamma-lines at energies of (205±5) keV, (328±5) keV, (370±5) keV, (660±5) keV, and (720±5) keV. The mixture of ^{137}Cs with other unknown radionuclide (-s) might be suspected. The malfunction of the device during measuring the spectrum is not considered in this report. However, similarity of the shape in the both energy regions of (270-420) keV and (580-780) keV can raise the questions about change in signal gain during the acquisition. The possible candidate for the source might be commonly considered either beta- or alpha-emitter with very low gamma-ray emission probabilities.
8	The spectrum suggests a ^{241}Am source. Since the 59-kev line is weak the source is partly shielded. If we had enough time we could analyse the ratios of the various peaks to decide the shielding, but we guess a few mm of lead. The two dose rate readings suggest that the source is in the centre of the truck and this combined with the shielding suggests that the source has strength of about 140 GBq assuming it's a point source.
9	Maybe plutonium containing mixture
10	Very high activities of heavily shielded ^{241}Am.
11	^{241}Am, 40 GBq, Shielded source
12	Most important nuclide in the source is ^{137}Cs, and we also think it consists of ^{241}Am and a small amount of ^{131}I. The most problematic is the peak around 330 keV, but we have decided on ^{51}Cr, though the 320 keV peak of that nuclide is far apart. The dose measurements suggest activity in the order of 1 – 2 MBq of ^{137}Cs.
13	^{137}Cs (1.23 MBq), ^{131}I (suspected), ^{241}Am (suspected)
14	Identified as ^{241}Am. The source is heavily shielded, roughly equivalent to 1.5 cm of steel.The activity is estimated (assuming the aforementioned shielding) to be approximately 200-300 MBq.
15	No data reported
16	The spectrum contains ^{137}Cs and possibly a small amount of ^{241}Am. There are also peaks at about 212 (^{228}Ac background?), 336 and 369 keV but they have not been identified.
17	Unidentified
18	This is obviously a heavily shielded ^{241}Am source.

2.1.2. Discussion

Responses from participants reflect the difficulty in identifying sources behind heavy shielding where their characteristic spectrum is distorted due to differing transmission across the energy range. A significant number however recognised the presence of ^{241}Am although the effect of the dominance of usually insignificant lines (such as that at 660 keV) is apparent in the number who indicate the presence of ^{137}Cs and other isotopes. A number of the participants correctly identified the presence of shielding and it was interesting to note that at least one was in position to estimate the thickness of the shielding present and a second indicated an ability to do so. Activity estimates were in all cases well below the actual amount present although this was expected and it is most probable that in an emergency situation, identification of the isotope plus recognition of shielding would result in an ultimate response little different to that which would have occurred had the exact activity been known. Misidentification of the isotope is possibly a little more consequential in that it must be assumed that the consequences of dispersal of an alpha emitter like ^{241}Am in an RDD would be potentially more problematic than dispersion of a gamma emitter such as ^{137}Cs (with similar problems in cases where ^{131}I was identified). One participant demonstrated the problem of there being no corresponding entries in the employed library despite having correctly identfied the peaks present resulting ultimately in a failure to identify although the analyst was able to hypothesise as to its possible nature (alpha emitter). Scenario 1 aptly served to demonstrate that an ability to identify an isotope in a field situation can be compromised due to the context in which the isotope is presented and the activity that may be present.

2.2 Scenario 2

Scenario 2 was intended to simulate an incident involving the siezure of an amount of weapons grade plutonium (WGPu). A number of incidents have been reported over the years involving varying quantities of such materials in a range of situations with perhaps the best known being the interdiction of several hundred grams of ^{6}Li and over half a kilo of mixed oxides of plutonium and uranium at Munich airport in 1994 (IAEA Database on Illicit Trafficing, and see Wallenius et al, 2007). Of this some 408 g was plutonium oxide of which 87% was fissile ^{239}Pu of 99.75% purity. Although the seizure of such materials would ultimately require or involve international assistance/authorities, it can be argued that any individual country should be in a position to conduct at least a preliminary analysis of the material for identification purposes and in that respect it was included in the MALRAD suite of scenarios.

The source for this scenario was considered to be exactly 100 g of of 25 year old (since last separation) WGPuO, sealed in a steel cylinder for the puposes of safe smuggling. The PuO volume was 8.69 cc (assumed density 11.5) and was, for the purpose of the simulation, in the geometric form of a perfect cylinder of dimensions 2 cm in diameter and 2.77 cm in height. This was then sealed in a steel cylinder of wall thickness 1 cm, external diameter 4 cm, and external height 5 cm. The PuO was presumed to consist of the following weight composition at the time of purification, this being typical for WGPu (Fetter et al, 1990).

^{238}Pu 0.005% (0.005 g)
^{239}Pu 93.3% (93.3 g)
^{240}Pu 6.0% (6 g)
^{241}Pu 0.4% (0.4 g)
^{242}Pu 0.015% (0.015 g)

The Pu source was then allowed to “decay” for 25 years to simulate Pu that was stolen from a respository for such materials or similar and daughters built up over that time were included if they had an activity of more than 10 Bq (see Table II). Non-Pu impurities in the initial source were assumed to be less than 0.3%. For the purposes of the scenario, the following specific activities were used: ^{238}Pu – 6.3E+14 Bq/kg, ^{239}Pu – 2.3E+12 Bq/kg, ^{240}Pu – 8.4E+12 Bq/kg, ^{241}Pu – 3.8E+15 Bq/kg, ^{242}Pu – 1.5E+11 Bq/kg. Based on the above, the following was assumed to be present after 25 years decay.

	Bq		Bq		Bq		Bq		Bq
^{238}Pu	2.585E+09	^{239}Pu	2.144E+11	^{240}Pu	5.027E+10	^{241}Pu	4.563E+11	^{242}Pu	2.25E+06
^{234}U	2.030E+05	^{235}U	5.281E+03	^{236}U	3.727E+04	^{241}Am	3.463E+10	^{238}U	8.72E-03
^{230}Th	2.360E+01	^{231}Th	5.279E+03	^{232}Th	2.308E-05	^{237}U	1.119E+07	^{234}Th	8.69E-03
^{226}Ra	8.631E-02	^{231}Pa	1.394E+00	^{228}Ra	1.259E-05	^{237}Np	1.693E+05	^{234m}Pa	8.67E-03
^{222}Rn	8.615E-02	^{227}Ac	3.062E-01	^{228}Ac	1.259E-05	^{233}Pa	1.681E+05	^{234}Pa	2.86E-05
^{218}Po	8.615E-02	^{227}Th	2.996E-01	^{228}Th	9.631E-06	^{233}U	6.712E+00	^{234}U	3.07E-07
^{214}Pb	8.615E-02	^{223}Fr	4.225E-03	^{224}Ra	9.616E-06	^{229}Th	4.168E-03	^{230}Th	2.30E-11
^{218}At	1.723E-05	^{223}Ra	3.021E-01	^{220}Rn	9.616E-06	^{225}Ra	4.131E-03	^{226}Ra	5.70E-14
^{214}Bi	8.615E-02	^{219}Rn	3.021E-01	^{216}Po	9.616E-06	^{225}Ac	4.105E-03	^{222}Rn	1.25E-13
^{214}Po	8.615E-02	^{215}Po	3.021E-01	^{212}Pb	9.616E-06	^{221}Fr	4.105E-03	^{218}Po	1.33E-15
^{210}Pb	1.456E-02	^{211}Pb	3.021E-01	^{212}Bi	9.616E-06	^{217}At	4.105E-03	^{214}Pb	0.00E+00
^{210}Bi	1.452E-02	^{211}Bi	3.021E-01	^{212}Po	6.159E-06	^{213}Bi	4.105E-03	^{218}At	1.30E-17
^{210}Po	1.338E-02	^{207}Tl	3.013E-01	^{208}Tl	3.455E-06	^{213}Po	4.017E-03	^{214}Bi	1.09E-13
		^{211}Po	8.461E-04			^{209}Tl	8.869E-05	^{214}Po	2.31E-13
						^{209}Pb	4.105E-03	^{210}Pb	1.06E-13
								^{210}Bi	5.91E-14
								^{210}Po	9.65E-14

Table II. Isotopes and activities based on 25 years decay and ingrowth of the 100 g of WGPuO for Scenario 2. Shaded isotopes with activities above 10 Bq were used in the simulation.

For the purposes of Scenario 2, it was supposed that the steel cylinder was counted suspended normally and coaxially over a HPGe detector as a preliminary step in its analysis and it was the result of this analysis which formed the basis for the scenario materials. The distance between the endcap of the detector and the bottom of the cylinder was 15 cm which would be a typical distance for measurements of this type. Self absorption by the PuO matrix was included in the simulation as was the 1 cm of steel shielding due to the cylinder itself. The detector was a standard coaxial HPGe detector with an aluminium endcap, dead layer of 0.5 mm, relative efficiency of 50% and a resolution of 1.9 keV at 1332 keV. The spectrum was between 10 keV and 2000 keV with a discrimation of 30 keV and 8192 channels (0.24292 keV/channel). The live time was 3600 seconds. No efficiency data was provided to the participants. Such a situation, due to lack of information of the geometry, would of course not facilitate generation of accurate efficiency values by any means. A point source spectrum was also provided containing ^{241}Am, ^{60}Co, ^{88}Y, ^{109}Cd and ^{137}Cs for the purpose of energy and shape calibration.

The analysis of Pu on a coaxial HPGe detector presents significant challenges for the analyst. These are related primarily to the complex nature of the spectrum, its domination by ^{241}Am in "old" samples, its being a material not often (if ever by most labs) encountered and the fact that most commercial software include, at best, a rudimentary library related to Pu. A

"normal" HPGe detector was chosen as it was considered that not all laboratories are in possession of the planar detectors on which such an analysis would be best performed. In general it was considered reasonable to hope that participants could:

- identify the source as being plutonium,
- could estimate whether or not the plutonium was weapons grade ("low burnup") or reactor grade ("high burnup") plutonium and;
- theoretically, estimate the age of the material since last separation.

The identification of significant amounts of old plutonium by HPGe gamma ray spectrometry is theoretically a relatively simple task given that the isotopes it is typically composed of emit a number of gamma rays but in practice the situation is complicated by the level of complexity of the spectrum. The most prominent signature in the spectrum is usually that of ^{241}Am at 59.5 keV which was clearly visible in the Scenario 2 spectrum even allowing for the 1 cm of steel shielding and the distance to the detector which served to attenuate this peak. In this context, the presence of ^{241}Am should have served as a strong indicator for the potential presence of the parent ^{241}Pu. The presence of the clearly defined strong singlet peak at 345.0 keV should also serve as indication of the presence of ^{239}Pu which would then allow confirmation of the presence of this isotope using a number of other lines, in particular, the 646 keV and 659 keV singlets. On this basis, identification of ^{239}Pu and ^{241}Pu based on ^{241}Am (in addition to ^{237}U) should have been relatively straightforward. Once ^{239}Pu was identified, it is quite reasonable to assume the presence of ^{238}Pu and ^{240}Pu.

Pu-241 has a limited number of gamma lines and the ones it does have are in the most complex (abd difficult) area of the spectrum at less than 100 keV. Identification is therefore facilitated mostly via the emissions of ^{241}Am and ^{237}U. Pu-242 is essentially impossible to identify using normal gamma ray spectrometry tools as it has only three lines of low energy which would have been both drowned out by ^{241}Am and heavily attenuated by the steel cladding. Pu-240 has some potentially useful lines such as those at 104.2 keV, 160.3 keV and 642.3 keV but these tend to be part of complex multiplets and it is ulikely that they would be found by an automatic search or identified as the correct isotope by the software. If the presence of ^{239}Pu had been determined however then a specific manual search for these lines would probably have confirmed the presence of this isotope which should, at any rate, have been assumed given the presence of ^{239}Pu. On this basis, identification of the material as

plutonium of one form or another should have been a relatively simple matter and a definitive identification should have been possible with a careful analysis of the spectrum.

One weakness of the MALRAD scenario was that the sample was simulated as PuO but did not feature the characteristic peak at 870.8 keV that has frequently been proposed for distinguishing PuO from metallic Pu. Although this peak has gained apparent acceptance as an identifier of PuO, the source of the peak and its being an identifier for the oxide state is a matter of some discussion (see Peurrung et al, 2001) and due to lack of information as to intensities etc, the decision was made not to include the peak.

Determining whether or not the plutonium present was high burnup or low burnup presents a more complex challenge as it involves assessing the $^{240}Pu/^{239}Pu$ relationship (low for low burnup or "weapons grade", high for high burnup or "reactor grade"). The accurate assessment of isotopic ratios in plutonium samples is a complicated task and this fact has resulted in the development of range of software packages and routines for conducting such measurements. The best known of these are MGA (and the related MGAU code for uranium isotopes) by Gunnink (1987), TRIFID (also known as GRPAUT) by Fleissner (1981) and FRAM by Sampson et al (1989) which are often employed in conjunction with low-energy, high resolution germanium detectors. Such systems do not require efficiency calibrations and can accurately produce isotopic ratios using, most often, low energy high resolution spectrometry (sub 600 eV at 122 keV). It was assumed that the majority of the MALRAD participants would not have had access to such codes and even if they had, the nature of the detector used in the scenario would have possibly complicated the task. It should be noted that subtleties such as different peak shapes for x-rays and gamma rays were not accounted for and the spectra as presented for MALRAD may not have been appropriate for use with specialised codes, in particular those represented by the MG++ suite. In this context, attempting to determine the composition of the sample would most likely have to have been achieved using conventional software tools to hand. In general, gamma ray spectra of plutonium can be divided up into a number of "standard" regions of analysis and some of these regions are those most commonly focused upon by custom codes. Full details of Pu analysis by gamma ray spectrometry may be found in a number of sources including, for example, Dragnev and Scharf (1975), Agarwal et al (2009), Keegan and Gehrke (2003) and the comprehensive if slightly older texts by Sampson et al (1982) and Sampson (1986). Although it is recognized that the participants could have devised any of a number of potential schemes for effecting

analysis, one common and potentially applicable scheme is outlined here. Perhaps the best option for estimating the $^{239}Pu/^{240}Pu$ relationship was the region around 640-650 keV. This part of the spectrum features peaks from both isotopes in close conjunction – eliminating problems associated with efficiency variations and varying attenuation caused by the cladding. This is in essence the only part of the spectrum that can be conveniently used for coaxial detectors and functions only in cases with large samples (such as MALRAD). The usefulness of the region is due to the gamma line at 642.3 keV from ^{240}Pu and the nearby 645.9 keV peak from ^{239}Pu. The ^{240}Pu line is interfered with by a line from ^{241}Am at 641.5 keV but the distance is such that it should be possible to deconvolute the multiplet using conventional software. This was performed using Interactive Peakfit® from Canberra and the results are displayed in Figure 5. As can be seen in Figure 5, relative to the "true" areas of the peaks, the results from deconvolution using general purpose tools are reasonable. Based on the two areas of 12982 for the ^{240}Pu peak and 64711 for the ^{239}Pu peak with emission intensities of 0.000013 and 0.0000152 respectively, an activity ratio of $^{239}Pu/^{240}Pu \approx 4.26$ could be estimated. Using the simple approach of employing specific activities of the respective isotopes indicates a mass ratio for $^{239}Pu/^{240}Pu$ of ≈ 15.55 ($^{240}Pu/^{239}Pu$ of ≈ 0.06) which should be sufficient to declare the sample to be low burn up weapons grade plutonium as opposed to high burn up reactor grade plutonium.

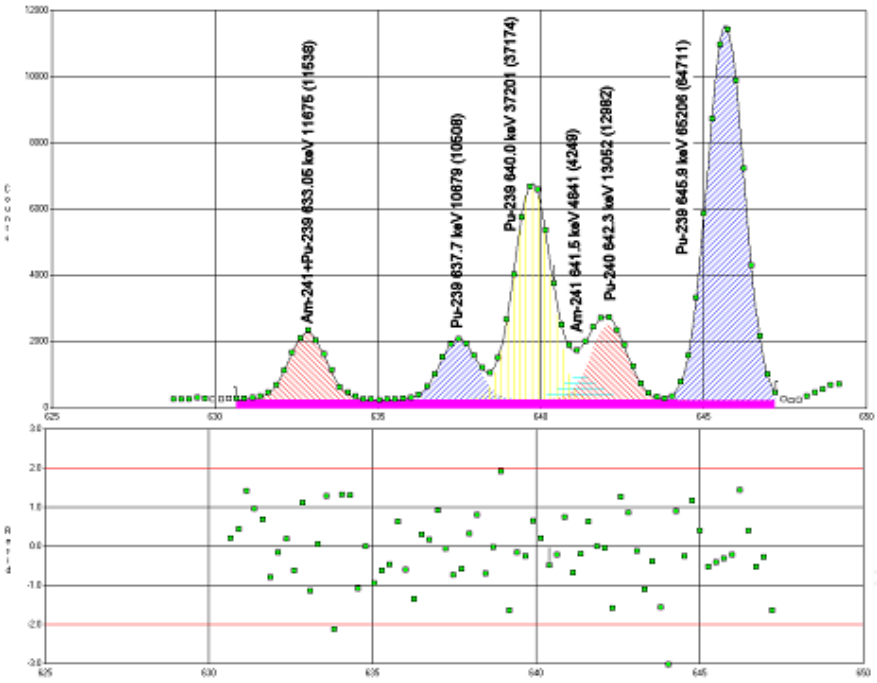


Figure 5. Deconvolution of the 630 to 650 keV region of the Scenario 2 spectrum. Determined areas provided in parenthesis with actual areas preceding.

Determining the age of a plutonium sample since last separation is not a trivial task and especially with the materials as provided to participants. Possible parent-daughter relations for plutonium are: $^{238}Pu/^{234}U$, $^{239}Pu/^{235}U$, $^{240}Pu/^{236}U$, $^{241}Pu/^{241}Am$ and $^{242}Pu/^{238}U$. In reality only a very limited number of these are of any use and the one that features most often is the $^{241}Pu/^{241}Am$ ratio. The problem is of course finding a region where ^{241}Am and ^{241}Pu have their own well separated peaks of similar energies which is not simple. A possible way around this is to find another isotope which facilitates the task and allows ^{241}Am to be expressed relative ^{241}Pu via an intermediary. The region between 143 keV and 151 keV is of potential interest in this regard containing peaks from ^{241}Pu, ^{241}Am and ^{239}Pu in close proximity although some are parts of complex multiplets.

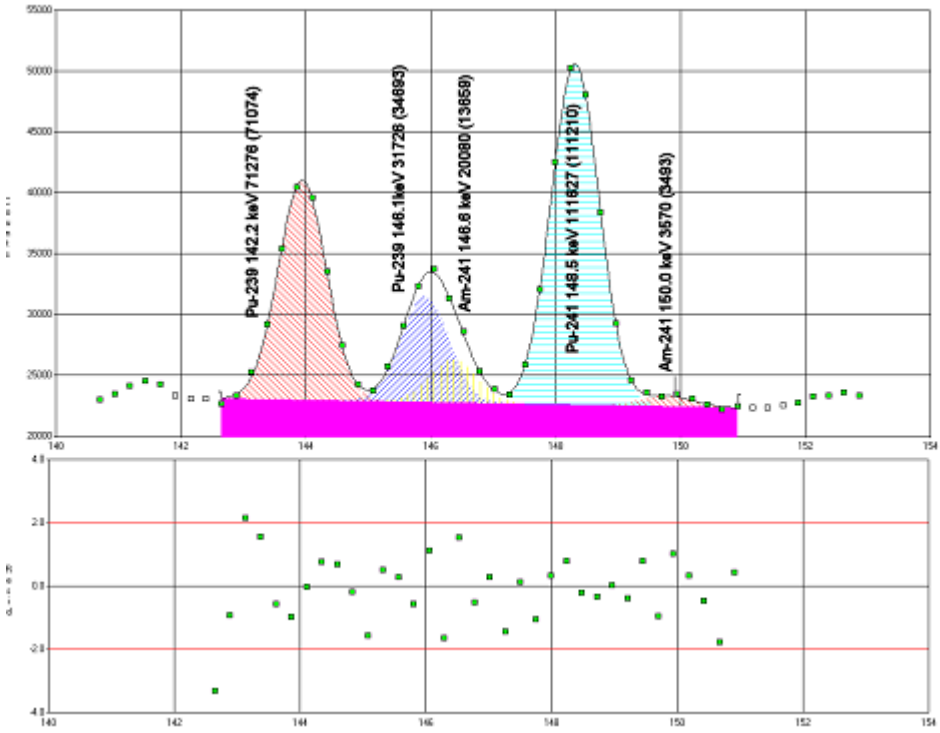


Figure 6. Deconvolution of the 142 keV to 152 keV region of the spectrum of Scenario 2. Determined areas provided in parenthesis with actual areas preceding.

As can be seen in Figure 6, conventional tools are reasonably sufficient to separate out the two main peaks of ^{239}Pu and ^{241}Pu but not the $^{241}Am/^{241}Pu$ doublet in the centre portion. Based on the two former one could estimate an activity ratio for $^{239}Pu/^{241}Pu$ based on areas and emission probabilities of 71074 and 0.000283 for ^{239}Pu and 111210 and 0.0001855 for ^{241}Pu. This ratio is approximately ≈ 0.418. The second part of the process would therefore be estimating the relationship between ^{241}Am and ^{239}Pu. This can be achieved using the 169.6

keV peak of ^{241}Am and the nearby 171.4 keV peak of ^{239}Pu. Using the values provided by this deconvolution provides an approximate ^{241}Am/^{239}Pu activity ratio of (13322/0.000173)/(57234/0.00011) = 0.148. Combining this with the earlier ^{239}Pu/^{241}Pu ratio of 0.418 provides an activity ratio for ^{241}Am/^{241}Pu of 0.0618 (or 16.1812 for ^{241}Pu/^{241}Am). Using a specific activity of 1.3E+14 Bq/kg for ^{241}Am and 3.8E+15 Bq/kg for ^{241}Pu provides a crude mass ratio ≈ 1.8067 (or ≈ 0. 5535 for ^{241}Pu/^{241}Am). Using the relationship provided by Wallenius and Mayer (2000) of ^{241}Pu/^{241}Am = 20.159X $^{-1.2071}$ for the ingrowth of ^{241}Am to the parent would thus provide an gross estimate of the age of the plutonium of ≈ 20 years which is a reasonable estimate given the data to hand.

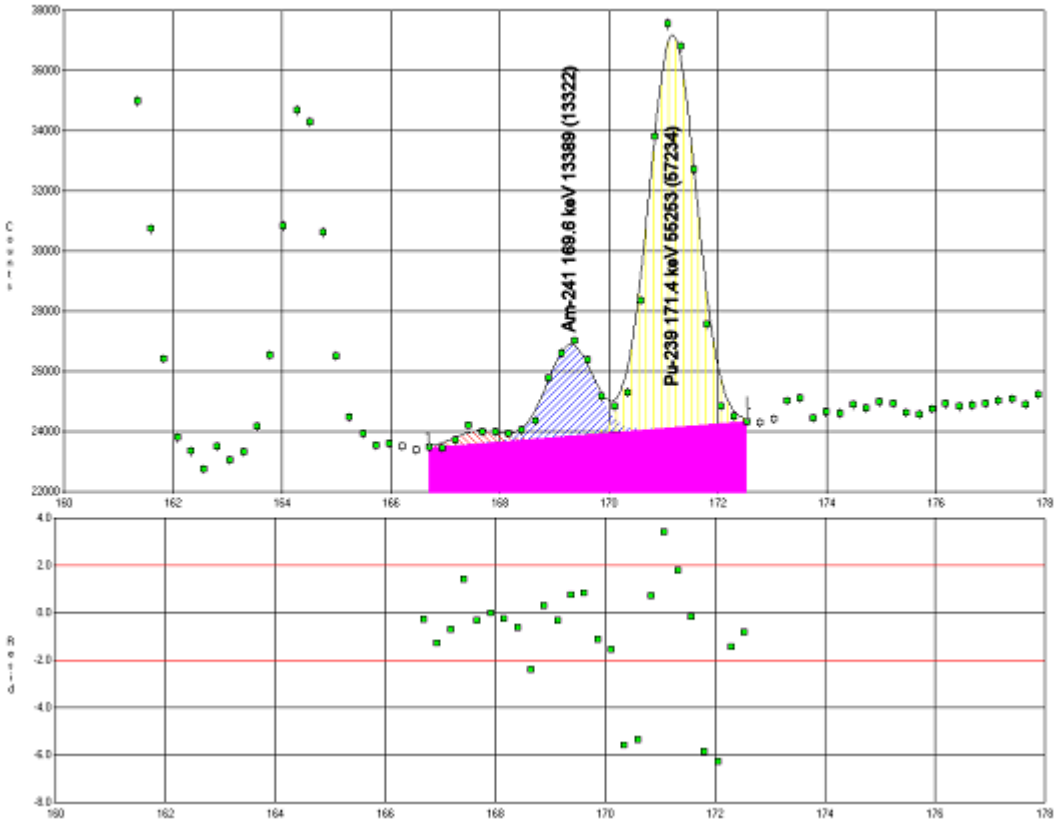


Figure 7. Deconvolution of the 166 keV to 174 keV region of the Scenario 2 spectrum. Determined areas provided in parenthesis with actual areas preceding.

2.2.1 Reported Results

Participant	Reported Data
1	Source identified from spectrum as ^{239}Pu. Source strength estimated at 0.6 GBq or 0.3 g (range 0.1-0.5 g) based on spectrum and detector information.
2	Participant withdrew
3	Participant withdrew
4	^{239}Pu , ^{241}Am, ^{240}Pu, ^{241}Pu
5	Unidentified
6	No data reported
7	The source is "weapon-grade" plutonium (^{239}Pu) of high activity. Presence of other Pu isotopes can be found in the gamma-spectrum: ^{240}Pu, ^{241}Pu with daughter ^{241}Am, and ^{242}Pu. Estimated activity of ^{239}Pu is of the order of 40 GBq (around 1 Ci).
8	The cylinder contains plutonium isotopes (238, 239, 240, 241) and ^{241}Am ingrown from ^{241}Pu. By comparing the peaks at 152 keV (^{238}Pu), 129 keV (^{239}Pu) and 148 keV (^{241}Pu) we conclude that it is weapons grade Pu, containing about 90% ^{239}Pu. As you do not want more than 7% ^{240}Pu in a weapon (it undergoes spontaneous fission), the enrichment of ^{239}Pu is probably more close to 93%. With an ultra high resolution HPGe we could probably deconvolute the ^{240}Pu peak near 104 keV and 160 keV and know the exact enrichment of Pu. The amount of plutonium in the cylinder could also be calculated if we knew if there is any other shielding present in the cylinder, or by comparing intensities of different peaks. The amount of plutonium present in the cylinder would also tell us the age of the plutonium by comparing ^{241}Am and ^{241}Pu.
9	Plutonium, probably ^{239}Pu.
10	The analysis suggests a mixture of ^{137}Cs and ^{241}Am.
11	^{239}Pu, ^{240}Pu (traces), 500 GBq, Weapons-grade plutonium
12	We assume that the spectrum is correct, though it is strange that there are no peaks above 1 MeV. We think we can distinguish ^{237}U in the spectrum, which is a daughter of ^{241}Pu. It therefore could be plutonium, but it is troublesome that we do not see the 113 keV peak of ^{239}Pu. But since we also see ^{233}Pa and ^{237}Np, we still think the source is plutonium, maybe enriched in 241Pu. The source also consists of ^{241}Am, another daughter of ^{241}Pu.There are a lot of other peaks in the spectrum. It may be other nuclides added to disguise the plutonium. Of these we think ^{177m}Lu and ^{113}Sn with daughter ^{113m}In are good candidates, since they have several peaks around the important peaks of ^{237}U.
13	Pu detected: ^{238}Pu ~ 0.01%; ^{239}Pu ~ 59.98%; ^{240}Pu ~ 37.78%; ^{241}Pu ~ 1.68%; ^{242}Pu ~ 0.52%; ^{241}Am ~ 1.48%
14	The source is identified as WGPu (isotopic composition: (93.6±0.2) % ^{239}Pu, (6.3±0.2) % ^{240}Pu, (0.112±0.002) % ^{241}Pu, and (0.006±0.002) % ^{238}Pu, (k=2)). It was last separated around Dec. 1983 (± 2 years).
15	No data reported
16	This sample contains ^{239}Pu, ^{240}Pu and ^{241}Pu and also ^{241}Am. There are also a lot of other peaks, e.g. from ^{137}Cs, that may be rests from the reprocessing, formed by spontaneous fission or added deliberately to "hide" the Pu.
17	Approximate weight percent, evaluated from spectrum analysis: ^{238}Pu 0.01%; ^{239}Pu 96.18%; ^{240}Pu 3.56%; ^{241}Pu 0.06%; ^{242}Pu unknown; 241Am 0.09% plus amounts of ^{237}U. ^{241}Am separated ~ 20.2 ± 6.5 years before measurement.
18	This is a spectrum dominated by more than 70 identified ^{239}Pu peaks. There is also ^{241}Pu present (one peak at 148.6 keV) and ^{241}Am with a few. Assuming now that the source is aged plutonium we can solve the Bateman equation and estimate the age since reprocessing to be 14 years. This means that the ^{241}Pu/^{239}Pu atom ratio at discharge was twice 0.15%, i.e. 0.30%. This is much closer to typical weapons grade plutonium with a ratio of 0.15% than to reactor grade plutonium with a ^{241}Pu/^{239}Pu atom ratio which is more like 10% at discharge. The source seems to be a 14 years old some 10 g piece of weapons grade plutonium.

2.2.2. Discussion

The spectrum of Scenario 2 should theoretically have been relatively easy to identify as being Pu of some sort. The difficulty with the source lay in trying to ascertain exactly what type of Pu was present and to derive further information as to isotope ratios etc. Most participants managed to pinpoint ^{239}Pu in the spectrum and some were in a position to attempt a deeper analysis as to whether or not the material was weapons grade. It is most probable that in such a situation, identification of ^{239}Pu, irrespective of whether or not one decides it is weapons grade, would be sufficienct to necessitate contacting international authorities. A significant number of the participants were in a position to ascertain that the material was weapons grade plutonium. More advanced analysis was not evident in the majority of the participants reports although some provided information as to isotopic composition which is not an elementary task with the material to hand. A few participants attempted to determine time since last separation and in two of these cases the estimates were quite close (within error) to the actual age of the plutonium. One participant derived a quite accurate value for the time of last separation in addition to having ascertained an accurate picture of the isotopic composition. It is quite satisfying to observe that one participant was willing to put forward the possibility that other isotopes had been included in an attempt to hide the nature of the source – an activity which has been encountered before primarily in "*spoofing*" or masking techniques where depleted or natural uranium is used to shield enriched uranium and confuse detectors for illicit purposes and which demonstrated an awareness of potential aspects of the problem presented which may not have been obvious to everyone. In general it is possible to hypothesise that there is a general lack of unfamiliarity with SNM in emergency situations – both in identifying what types of material are present and in what information can be extracted from such samples even using relatively unsophisticated software. The argument that the probability of such materials being encountered by most organizations is very low can be countered by the fact that there have been more incidents of interdicted plutonium than there have been of RDD's for which practicing and training is conducted.

2.3 Scenario 3

Scenario 3 was intended to simulate the use of radiation for murder such as has occurred in a number of cases but of most relevance in this instance is the incident where a Chinese nuclear scientist, Gu Jiming, employed ^{192}Ir pellets in an attack on a business rival. Having used forged papers to acquire an industrial device containing ^{192}Ir, the source was then placed in the ceiling panels in the hospital office of the victim. The victim reported symptoms including memory loss, fatigue, appetite loss, headaches, vomiting, and bleeding gums. Another 74 staff members of the hospital, including one pregnant woman, also exhibited symptoms. Gu was convicted for the crime on the 29th of September 2003 (Nature, 2003). The context of the placing of the source for Scenario 3 was taken from the situation involving the exposure of a man in Russia as a result of a 1.3 Ci ^{137}Cs source having being maliciously placed in the door of his truck as reported by Sevan'kaev et al (1999). The source in Scenario 3 consisted of the isotope ^{192}Ir in the form of brachytherapy seeds. The source was assumed to have been an effective point source of 11.1 GBq (300 mCi) of ^{192}Ir placed in the car seat of the victim. The shielding provided by the car was assumed to be equivalent to 4 mm of iron (taking into account the construction of the car itself plus shielding provided by the seat of the car). Self absorption within the seeds was assumed to be negligble. A point source spectrum of ^{241}Am, ^{137}Cs and ^{60}Co was also provided for energy and shape calibration. Dose measurements were also taken at a point 2 m from the source (1.8 m from the car + 20 cm to the source) where the dose rate was 229 μSv/hr and at 4 m from the source where the dose was 57 μSv/hr. The detector used in the scenario was a CdZnTe detector of 3 cm^3 volume with a supposed resolution at 1332 keV of 16 keV. The spectrum was taken over 4096 channels covering the energy range 10 keV to 1500 keV (0.36376 keV/channel) for a period of 60 seconds. Random statistical noise was added to the spectrum but no background. As a follow up, the same source/shielding configuration was used in conjunction with a HPGe detector of 50% relative efficiency and 1.9 keV resolution at 1332 keV over 8 k channels between 10 and 1500 keV (0.18189 keV/channel) for the same time period. Assuming correct identification of the isotope as ^{192}Ir, it should have been possible to derive an estimate of activity based upon the standard formulae as presented earlier in this text. The participants had been informed that two measurements were made - the first being 1.8 m from the side of the car where the dose was 229 μSv/hr and one 2 m further back where the dose was 57 μSv/hr. Using a gamma constant for ^{192}Ir of 0.1394 and the two distances from the source combined with the two dose measurements provides activity estimates of 5.3 GBq and 5.9 GBq which are reasonable estimates of the source activity of 11.1 GBq allowing for the thin shielding present and the

inaccuarcy of the source-meter distance. The identification of the source as ^{192}Ir should not have presented significant problems. Although the doublet at 201 keV to 206 keV is probably unresolvable the peak should be identified as 205 keV which is one of the characteristic peaks for ^{192}Ir. The quadruplet at 280 – 320 keV is, given a reasonabe shape calibration and the better resolution of CdZnTe, easily deconvoluted (see Figure 8.) and provides further useful information as to the identity of the isotope. The triplet between 580 – 620 keV is also automatically resolved (Figure 9) and the information from these two areas should have been sufficient to facilitate a positive identification.

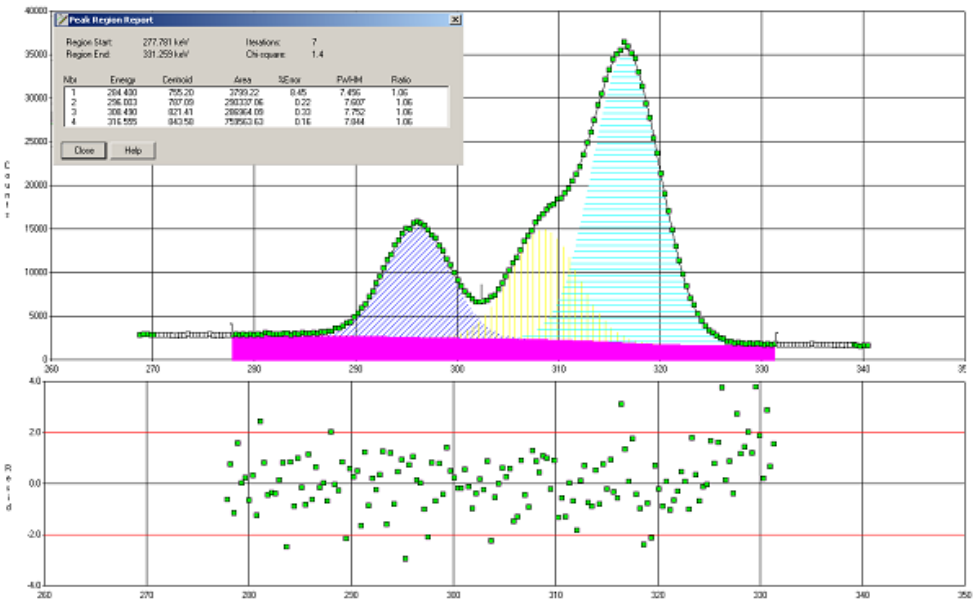


Figure 8. Automatic deconvolution of the quadruplet in the region of 280 keV to 320 keV.

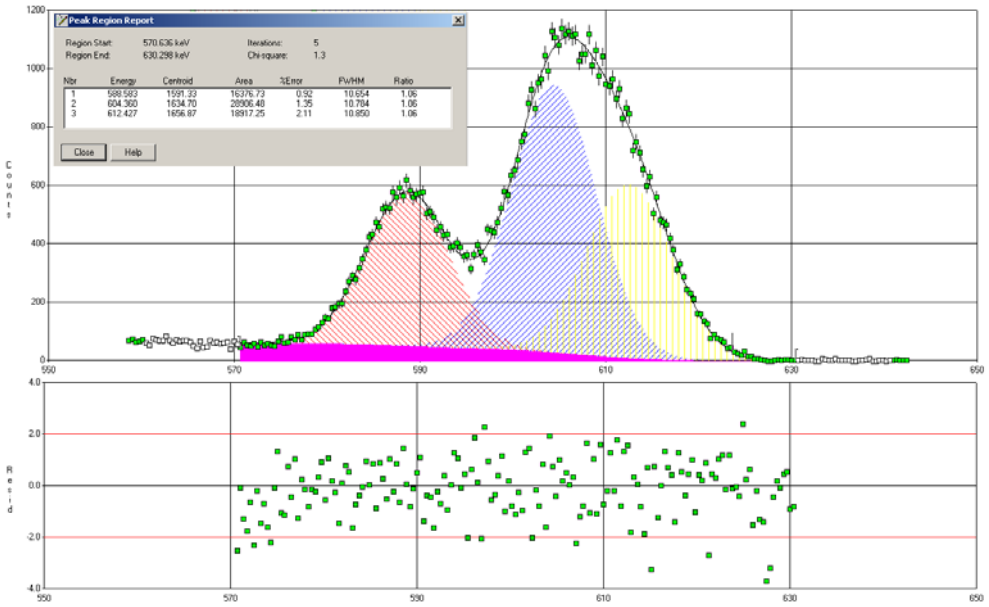


Figure 9. Automatic deconvolution of the triplet between 580 keV and 620 keV.

2.3.1 Reported Results

Participant	Reported Data
1	Source identified as ^{192}Ir from spectrum. Source strength estimated at 0.19 Ci or 7 GBq from dose rate measurements. The source strength is consistent with that of a low dose rate brachytherapy source. This seems consistent with the exposed person's occupation as a scientist in a large medical research facility.
2	Participant withdrew
3	Participant withdrew
4	^{192}Ir
5	Unidentified
6	No data reported
7	The source is ^{192}Ir. The estimated activity is about 7 GBq according to dose rate measurements on site.
8	The source is ^{192}Ir. The dose-rate readings suggest a dose rate of about 0.1 mSv/h in contact with the source. This suggests that the source is either partly shielded with lead, or is an old industrial source. The calculated dose rate is too low to give radiation sickness symptoms. It may be that the sick person has tried to take out a fresh source (containing GBq's of ^{192}Ir) and suffered a high dose. A 1500 GBq point source of ^{192}Ir has a dose rate of about 170 mSv/hr at 1 m distance. The dose rates are obviously much higher in contact.
9	Medical or industrial source of ^{192}Ir.
10	Analysis suggests ^{192}Ir.
11	^{192}Ir, 7 GBq, Brachytherapy wire
12	This is most probably ^{192}Ir. Assuming the source being 20 cm inside the car then the dose measurements suggests an activity of 8.5 GBq.
13	^{192}Ir, 6.3 GBq
14	The source is identified as ^{192}Ir. The activity is estimated to be at least 5 GBq.
15	No data reported
16	The activity is ^{192}Ir. The dose rate 10 cm from the source should be about 90 mSv/h.
17	^{192}Ir source of activity about 18 GBq
18	There is a (most probably) medical therapy source of around 0.2 Ci ^{192}Ir just inside the car. A typical amount sold for medical applications (brachytherapy) is 1-10 Ci so it is most probably taken from the medical research facility where the scientist was working. Industrial sources for radiography are normally one or two orders of magnitude larger.

2.3.2. Discussion

The vast majority of participants readily identified the source as ^{192}Ir and most were in a position to estimate activity even with a low-resolution spectrum. It was satisfying to observe that some participants used the ancilliary information provided in the scenario description (such as the location) to attempt to assign a source type (brachytherapy source) which is of course an important consideration in response to such situations. Activity determinations were most probably satisfactory for emergency response to this type of scenario.

2.4 Scenario 4

The purpose of this scenario was to simulate the use of irradiated graphite in a malevolent act. Such materials have been employed maliciously before, in particular the use of irradiated graphite under the driver's seat of a victims car inflicting a sustained 0.25 - 0.30 Gy dose to his spinal bone marrow and 4 -5 Gy to his testes (Mullen, 1987). The material was included in MALRAD due to its being possibly less securely guarded than high level materials (and therefore easier to steal or obtain) and its being an interesting source in relation to identifying the material. The scenario intended to simulate a situation where the material had been spread over an area and in-situ measurements were made in an attempt to identify the material. 1 kg of graphite of density 2 g/cm was assumed to have been spread over 5000 cm^2 to an average thickness of 1 mm. Due to there being little available information as to the actual activity of activated graphite, the work of Ancius et al (2005) was used and the graphite for Scenario 4 was assumed to have been 10 years old. Calculations for this time period indicate no appreciable build up of daughter products. The activity details of gamma emitting isotopes in the dispersed graphite are contained in Table III.

Isotope	**Total activity Bq**
^{60}Co	1.9E+07
^{244}Cm	1.6E+07
^{137}Cs	1.6E+05
^{154}Eu	1.1E+05
^{155}Eu	1.8E+04

Table III. Isotope content of the dispersed source of Scenario 4.

A 3 x 3 NaI detector (10 – 2500 keV, 7% @ 661 keV, 1.2158 keV/channel, 2048 channels) was suspended 50 cm above the planar source and a spectrum taken for a period of 20 minutes. A point source spectrum of ^{241}Am, ^{109}Cd, ^{137}Cs, ^{88}Y and ^{60}Co was also provided. No background was added. The primary features of the spectrum as provided were the two characteristic peaks of ^{60}Co at 1173 and 1332 keV which completely dominate the spectrum. The higher activity of this isotope plus the strength of its emissions tended to obscure most other features of the spectrum although the 661 keV peak of ^{137}Cs and the 123 keV peak of ^{154}Eu were theoretically visible. The sub 100 keV region was dominated primarily by x-rays of the Eu isotopes. It is doubtful whether successful identification of the isotopes involved other than ^{60}Co and ^{137}Cs could be conducted based on the spectrum to hand or whether or not the material itself would be identified for what it was. A strong potential existed for the

misidentification of the two lower energy peaks as perhaps ^{57}Co or other nuclides. As a follow up, the same source and point source were "measured" on a HPGe detector (50% nominal rel. efficiency, 1.9 keV at 1332 keV, 0.30395 keV/channel) of 8k channels over the same energy range for the same time period.

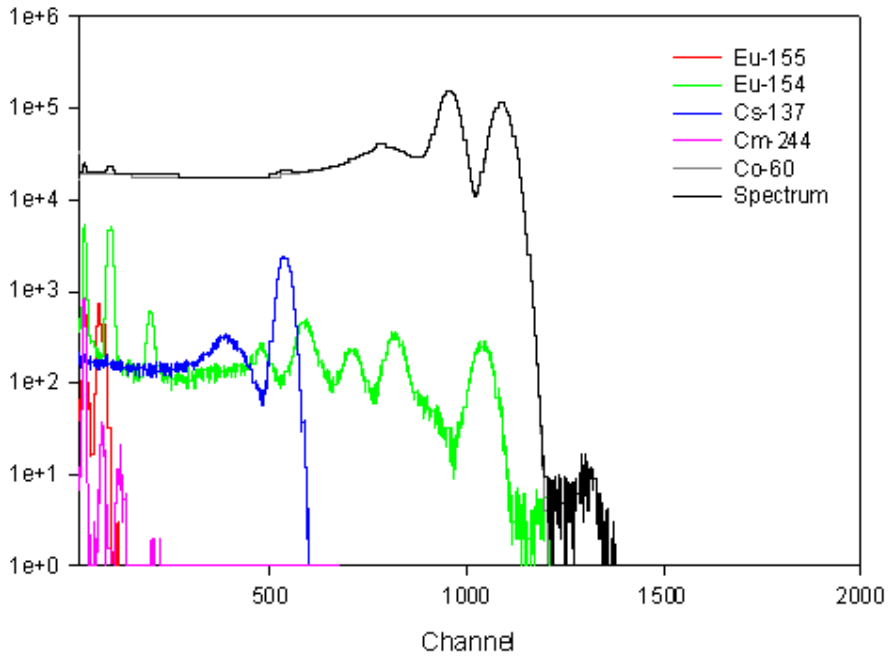


Figure 10. Total NaI spectrum for Scenario 4 with component spectra for individual constituent isotopes.

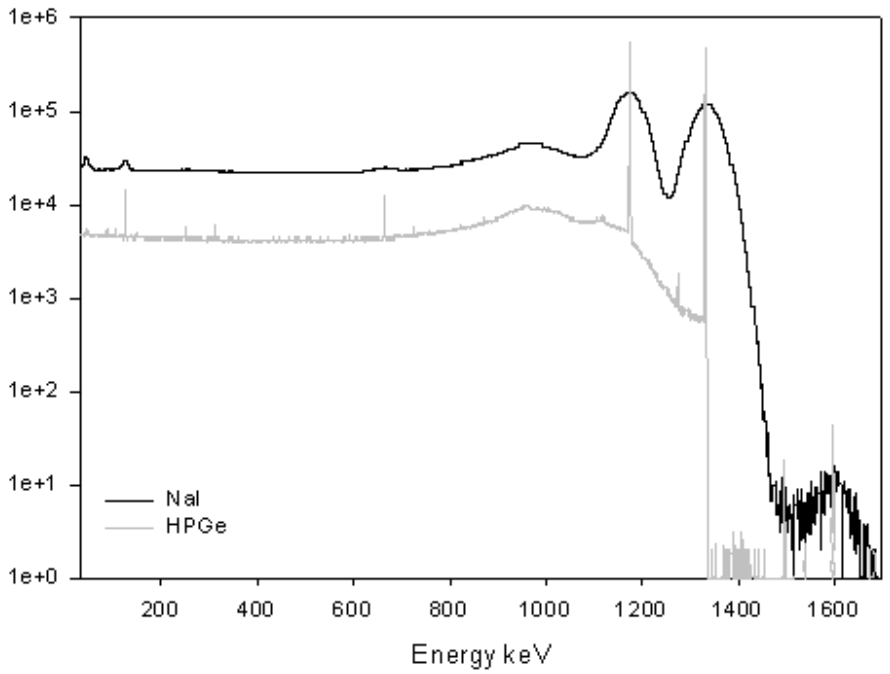


Figure 11. Comparison of NaI and HPGe spectra of the source for Scenario 4.

2.4.1. Reported Results.

Participant	Reported Data
1	Source identified from spectrum as ^{60}Co mainly, with traces of ^{57}Co and ^{137}Cs. Source strength of ^{60}Co estimated from dose rate measurements at 0.5 mCi or 0.2 MBq. Might be an old low dose rate brachytherapy source, but there are many possibilities.
2	Participant withdrew
3	Participant withdrew
4	^{60}Co,other peaks inconclusive.
5	^{60}Co
6	No data reported
7	The source is ^{60}Co. The estimated activity is about 20 MBq according to dose rate measurements on site.
8	The black powder contains ^{60}Co with traces of what seems to be ^{137}Cs. It's a bit strange that ^{137}Cs is there. Can it be that the detector is contaminated? It is difficult to say anything about the amount of ^{60}Co present since we do not know the distance between the dose rate meter and the powder, or the spreading of the powder.
9	^{60}Co, cobalt-based powder.
10	The analysis suggests high levels of ^{60}Co.
11	^{60}Co, ^{57}Co (traces), 50 MBq
12	The source is predominantly ^{60}Co, but there are also some other nuclides which we think are ^{137}Cs and ^{57}Co. If we assume a large area is contaminated, the activity would be 0.1 GBq/m^2 of ^{60}Co, 0.7 MBq/m^2 of ^{137}C and 0.2 MBq/m^2 of ^{57}Co.
13	^{60}Co 20.3 MBq; ^{137}Cs trace activity; ^{57}Co trace activity
14	The source is identified as ^{60}Co, with a minor contamination of ^{57}Co. In addition there is a small amount of ^{137}Cs. Furthermore, there are a few peaks in the spectrum that are not positively identified that may call for further investigation of the surroundings and possibly using high resolution gamma spectrometry. Assuming the dose rate was measured at 0.5 m a rough estimate gives an activity of approximately 20 MBq.
15	No data reported
16	The activity is ^{60}Co. There might be a very small amount of ^{137}Cs as well but this is uncertain.
17	No report for this scenario
18	The source is a detector calibration kit sized sample of essentially ^{60}Co. Small amounts of other common calibration nuclides are also seen.

2.4.2. Discussion

Scenario 4 was always potentially difficult given both the nature of the spectrum and the material involved. The low resolution of the spectrum plus the disparate intensities of the gamma line spresent all served to complicate the identification. All participants were in a position to pinpoint ^{60}Co and some were able to report ^{137}Cs although a number of participants suspected that th e661 keV peak was actually a single escape from the 1173 keV line of ^{60}Co. Beyond these two isotopes, ^{57}Co appears to have been the primary candidate for the visible low energy peaks in the spectrum. Scenario 4 along with Scenarios 5 and 7 was a scenario where the source was actually visible – reported as a "black powder" by cleaners and

indeed pictured in the scenario materials as distributed. In combination with the context of the occurrence, in relation to suspicious activities at nuclear facilities earlier, it was hoped that participants may have narrowed their thinking to a black granular material, possibly sourced from a nuclear facility, displaying significant (but not particularly dangerous) levels of ^{60}Co, ^{137}Cs and other isotopes. In which case irradiated graphite could theoretically have turned up as a candidate. Although literature material on irradiated graphite is not very common, the usual presence of ^{60}Co, ^{137}Cs and Eu isotopes is fairly well described in available materials and it was hoped this might have spurred participants on towards hazarding a guess. Irradiated graphite has featured before in malevolent acts, is a substance that could theoretically be viewed as attractive (from a security point of view) to activists and for which significant amounts exist in some countries. Activity estimates from most participants were quite good.

2.5 Scenario 5

This scenario involved the placing of a radioactive source on a bus intended to be representative of the type of situations where radioactive sources have been left in public places for whatever purposes. A ^{99}Tc generator was chosen largely due to the relatively easy availability of such materials. The source in this case was a standard medical ^{99}Mo/^{99m}Tc generator. For the purpose of the exercise the source was assumed to be a 10 day old generator whose activity was 40 GBq at time 0. After 10 days the activity was 40 x 0.0804 ^{99}Mo, 40 x 0.0775 ^{99m}Tc (3.216 GBq ^{99}Mo and 3.1 GBq ^{99m}Tc). The detector was a typical handheld 2 x 2 inch NaI detector, of resolution 7% at 661 keV. The spectrum was taken one meter from the source for a period of 10 mins over 2048 channels covering 10 keV to 2500 keV (1.2158 keV/channel).

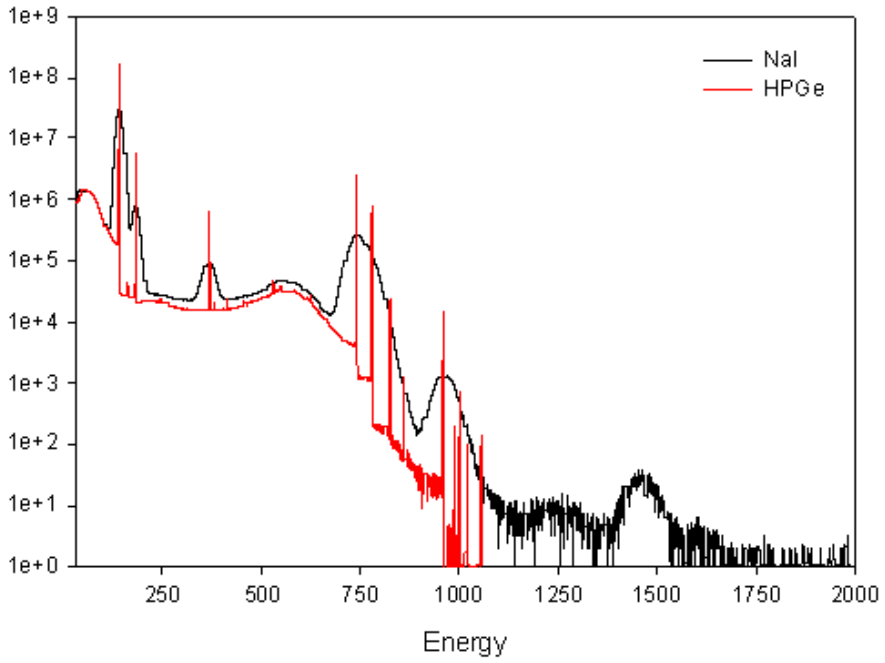


Figure 12. Comparsion of provided and high resolution (no background) spectra from Scenario 5.

A background signal was also added to the spectrum manifesting itself primarily as a ^{40}K peak at 1460 keV. A point source spectrum was provided of ^{241}Am, ^{109}Cd, ^{137}Cs, ^{88}Y and ^{60}Co at a distance of 10 cm from the detector. The follow up spectrum was that of the same source using a HPGe detector (1.9 keV @ 1332 keV) 50 % relative efficiency using 8192 channels covering the same energy range. A dose rate measurement was made at 1 m distance and this was 131 µSv/hr. Determination of activity in this instance should have been relatively simple in this case. If the assumption was made that the isotope was ^{99}Mo/^{99m}Tc then given the half-lives it would be reasonable to assume that the two isotopes were in transient equilibrium and

therefore of approximately equal activities. Lists of gamma rate constants for isotopes typically provide data for parents including short lived daughters in equilibrium. Data for ^{99}Mo is 0.04426 providing an activity estimate of 2.9 GBq ^{99}Mo and approximately the same activity for the daughter.

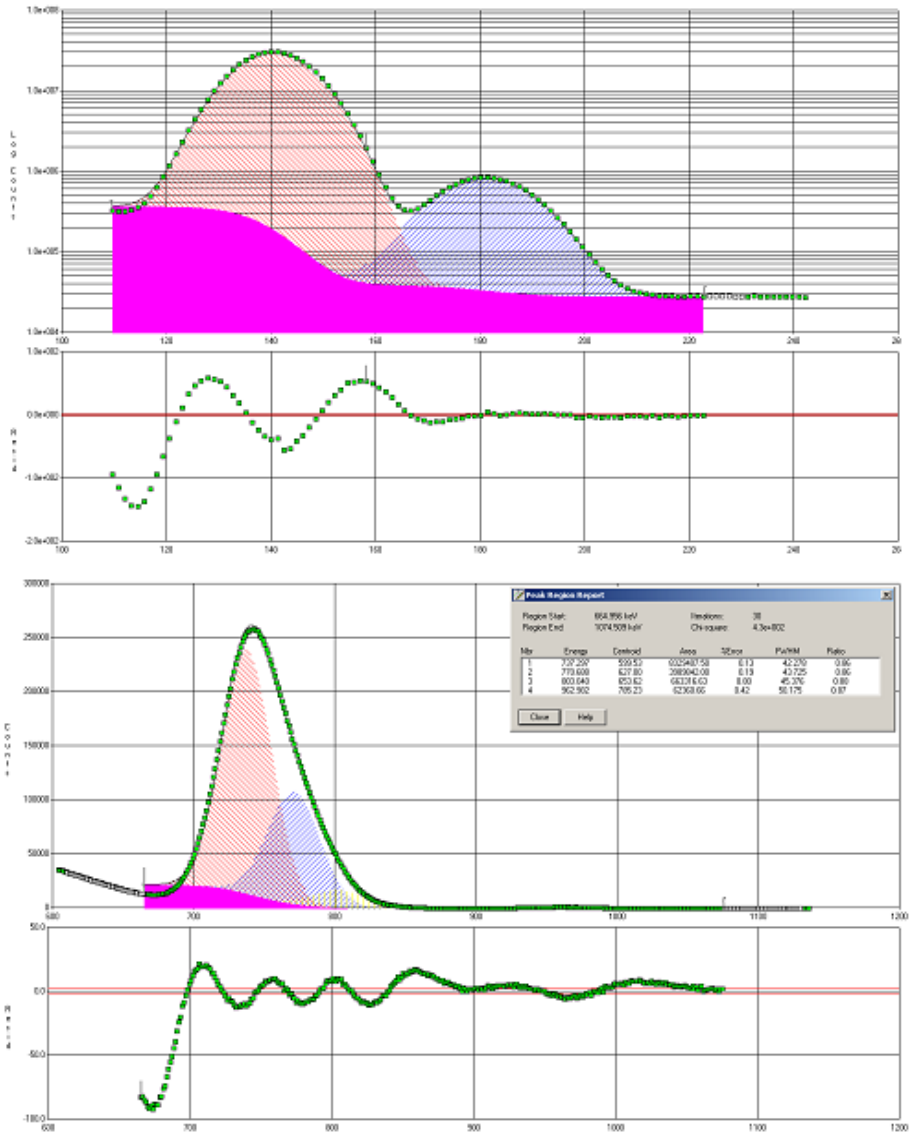


Figure 13. Deconvolution of the regions between 130 keV and 200 keV (top) and 660 keV and 1000 keV (bottom) for Scenario 5.

Identification of the source of Scenario 5 should have not proven too problematical. The large combined peak at 140 keV for ^{99m}Tc and ^{99}Mo was readily identifiable as was the peak at 181 keV (Figure 13) and the area between 600 and 1000 keV with a number of peaks should have facilitated identification as ^{99}Mo with ^{99m}Tc as assumed.

2.5.1. Reported Results.

Participant	Reported Data
1	Source identified from spectrum as ^{99}Mo. Source strength estimated from dose rate measurements at 0.20 Ci or 7 GBq. The source strength suggests that this could come from a diagnostic isotope generator.
2	Participant withdrew
3	Participant withdrew
4	No reliable/conclusive results
5	^{99}Mo
6	No data reported
7	The source is ^{99}Mo. The estimated activity is about 6 GBq according to dose rate measurements on site.
8	This is a ^{99}Mo-^{99m}Tc generator. Since white powder is visible (most probably Al_2O_3 which is used on a column to separate Tc from Mo) the column must be broken. But, since the radioactivity symbol still is there, some of the lead shielding still is present. Since it is dripping from the package it may indicate that this is a so-called "wet-generator". A "wet-generator" contains all the liquid needed for all the elutions during the life-time of a generator. This may indicate that the generator is fairly fresh. The amount of ^{99}Mo present in a generator varies considerably (GBq levels).
9	^{99}Mo/^{99m}Tc. Probably a ^{99m}Tc generator (based on a source of ^{99}Mo) was stolen, destroyed and white powder taken in the form of molybdate.
10	The analysis suggests high levels of ^{99m}Tc and ^{99}Mo. That the source is liquid is plausible.
11	^{99}Mo, ^{99m}Tc, 3 GBq
12	This is ^{99}Mo/^{99m}Tc. The 140 keV line is strong and we assume equilibrium of the activity. Then, based on the dose measurement, the activity of the source is approximately 3.3 GBq of each nuclide.
13	^{99m}Tc + ^{99}Mo 3.1 GBq
14	The source is identified as ^{99}Mo/^{99m}Tc.The activity is estimated to be at least 3 GBq.
15	No data reported
16	The sample contains ^{99}Mo and its daughter ^{99m}Tc. The dose rate at 10 cm distance should be about 13 mSv/h.
17	No report for this scenario
18	^{99}Mo (including ^{99m}Tc) gives 6.36 μSv/h per MBq unshielded at 1 m distance. Here 99% is due to bremsstrahlung from the beta decay of ^{99}Mo. From this we can estimate from the 131 μSv/h detected at 1 m (ignoring a 0.1 μSv/h background) the source to be some 20 MBq. A typical technetium cow (sometimes called moly-cow) used at hospitals contains some 200 MBq at start so this seems to be a finished cow (about one week old). The source is a "last week" technetium cow with a current activity of some 20 MBq ^{99}Mo (T1/2 = 2.75 d).

2.5.2 Discussion

Scenario 5 was potentially the simplest of all the scenarios in that the spectrum was relatively simple, the physical description of the source was such that participants could narrow their candidates and there was no effective shielding. The white powder as described, along with the "wet" nature of the material was intended to indicate a $^{99m}Tc/^{99}Mo$ generator and it was satisfying that at least some participants were willing to take this information on board and use it in their conclusions. All participants were able to identify the source for what it was and activity estimates were realistic in the majority of cases. There was some potential for difficulty in that while the characteristic spectrum of ^{99m}Tc may have been known to many due to its use as a tracer, the presence of ^{99}Mo peaks may have caused confusion although it appears that most participants were confident in their identification. In one report where the activity was underestimated, bremsstrahlung had been incorporated into the dose measured. Although this demonstrates thorough knowledge of the situation, the effect of beta particles had been stated in the exercise instructions to have not played a role in the scenario simulations but the logic of the participant was quite correct and it was quite encouraging to see this aspect being considered.

2.6 Scenario 6

The sixth scenario was directed towards simulating a situation involving theft of a source (either on purpose or by accident) which in this instance was the radiographic isotope ^{75}Se. The source consisted of 1480 GBq (40 Ci) of ^{75}Se which is a midrange activity for ^{75}Se based industrial radiography sources. The source was positioned within a pile of scrap such that an effective shielding of 10 cm of aluminium was covering the source. The detector was a 3 cm^3 CdZnTe detector positioned 5 m from the source (including the 10 cm of Al). The detector had a relative efficiency of 1% and a resolution of 16 keV at 1332 keV. A spectrum was taken for 20 seconds over 2048 channels covering 10 keV to 1500 keV (0.72755 keV/channel). No background was added. A low energy scattering continuum was added to the spectrum. As follow up, a HPGe spectrum was taken under the same conditions as for the CdZnTe spectrum over 8192 channels for the same energy range (0.18189 keV/channel). The background corrected dose rate at a distance of 5 m from the pile surface was 0.802 mSv/hr and at 10 m from the pile surface 0.201 mSv/hr. The presence of shielding of an unknown thickness complicates the activity estimate in this instance. A crude estimate based on the two dose measurements taken and assuming no shielding would provide activity estimates of 302 GBq and 303 GBq which are substantially lower than the actual value.

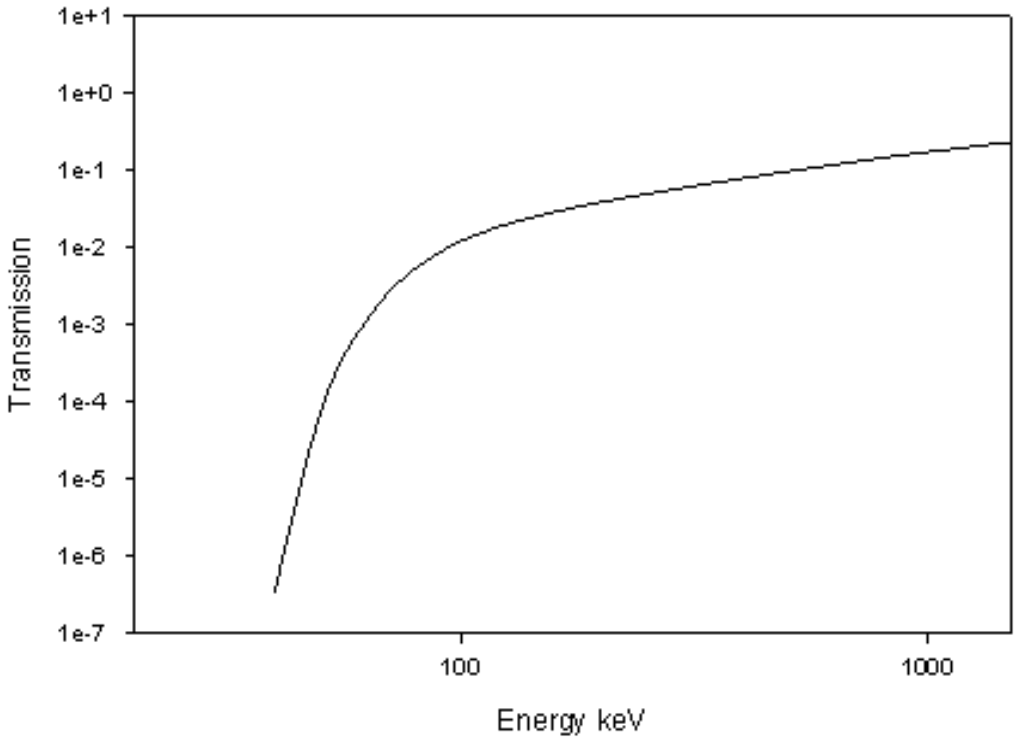


Figure 14. Transmission curve for Scenario 6 in the presence of 10 cm of aluminium.

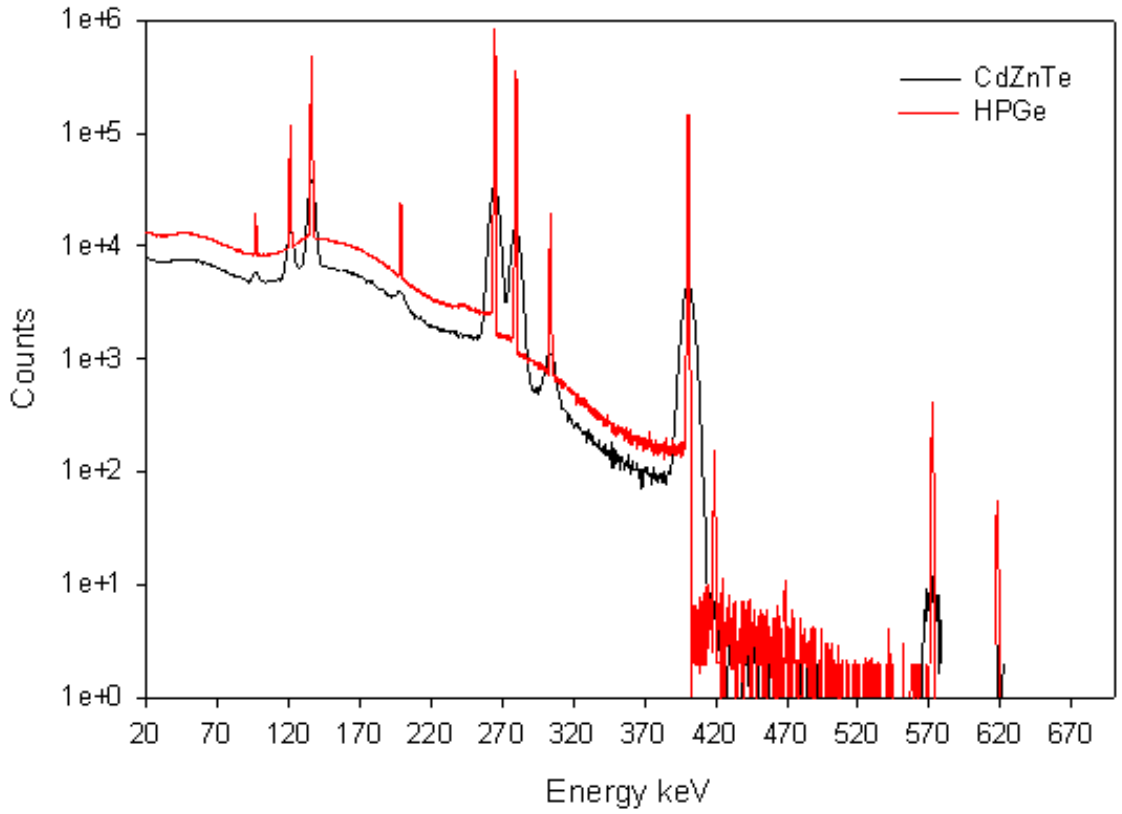


Figure 15. Comparison of CdZnTe and HPGe spectra for the ^{75}Se source of Scenario 6.

Identification of the source as ^{75}Se should, in itself, be a simple matter given that a number of clearly resolved strong singlets are present in the spectrum. It is of course possible that analysts may not have been familiar with the isotope or perhaps their library did not contain it but in instances where it did, it is difficult to see what else it could have been confused for.

2.6.1. Reported Results.

Participant	Reported Data
1	Source identified as ^{75}Se from spectrum. Source strength estimated at 10 Ci or 0.4 TBq from dose rate measurements. The source strength suggests that this is an industrial radiography source that is about a year old.
2	Participant withdrew
3	Participant withdrew
4	No reliable/conclusive results.
5	^{75}Se,
6	No data reported
7	The source is ^{75}Se. The estimated activity is about 380 GBq (>10 Ci) according to dose rate measurements on site.
8	The source is ^{75}Se. Since the dose rate is about 0.8 mSv/hr at a distance of 5 m from the pile surface, and about 0.2 mSv/hr 5 m back, the source is located near the surface of the pile. If we guess that the source has about 1 cm of iron in front of it, it's strength could be about 700 GBq.
9	^{75}Se. Probably the source was ^{75}Se capsules (a metal combined with selenium) used in pipline gamma radiography which were thrown away.
10	Our analysis suggests ^{75}Se.
11	^{75}Se, 350 GBq, Industrial source
12	All the lines in this spectrum can be explained by a single nuclide, ^{75}Se. Based on the dose measurements the source is at least 410 GBq.
13	^{75}Se 568.5 GBq
14	The source is identified as ^{75}Se (after a recalibration of the spectrum with respect to energy). The activity is estimated to be at least 400 GBq.
15	No data reported
16	The source is ^{75}Se. The dose rate should be about 80 mSv/h at 0.5 m distance and 8 Sv/h at 5 cm distance, i.e. in this scenario the source is so strong that it will require a lot of radiation protection measures to remove it.
17	^{75}Se source of activity about 370 GBq.
18	The source is a ^{75}Se source of about 100 GBq at the surface of the metal scrap pile. It is probably a lost source from a sheet metal thickness gauge used in industry.

2.6.2 Discussion

The organizers had considered that ^{75}Se would have been representative of a range of "exotic" industrial isotopes that can turn up as part of specialized applications and that possibly in this context it would have proved a challenge. However all participants managed to identify it for what it was. Activity estimates were in all cases low as a result of the shielding present but it is doubtful whether or not the difference between estimated value and actual would have resulted in any difference in the type of response initiated.

2.7 Scenario 7

The source in this scenario was considered to be an amount of highly enriched uranium and was intended to represent a situation whereby a laboratory may be asked to analyse a sample of nuclear material which it may be assumed is outside the suite of usual activities of many labs and yet represents a situation that may feasibly arise. The basis of the source was the composition of the smuggled uranium seized in Bulgaria in 1999 (LLNL, 2001). The isotopic composition of this uranium was as, at the time of its seizure, as displayed in Table IV. For MALRAD, all isotopes except those of uranium were removed from the consideration and the uranium composition of the material in the Bulgarian sample was assumed to be that at the time of last purification. This was then allowed to decay for a period of ten years and the daughters calculated. The sample was considered to be 10 g which was then counted 10 cm above the surface of a HPGe detector. The activities of the uranium isotopes were derived from the mass composition as per Table V. The activities of the isotopes and ingrown daughters are displayed in Table VI and any daughter with an activity over 20 Bq was included in the simulation.

^{242}Pu 4.6x10^{-9}	^{238}U 13.9	^{231}Pa 4.6x10^{-7}
^{241}Pu 7.9x10^{-9}	^{236}U 11.9	^{230}Th 2.0x10^{-5}
^{240}Pu 2.6x10^{-8}	^{235}U 72.7	^{229}Th 9.9x10^{-10}
^{239}Pu 2.2x10^{-7}	^{234}U 1.1	^{228}Th 2.6x10^{-8}
^{238}Pu 1.1x10^{-8}	^{233}U 2.9x10^{-5}	^{227}Ac 3.3x10^{-11}
^{137}Cs 4.6x10^{-10}	^{134}Cs 3.3x10^{-13}	^{125}Sn 5.3x10^{-11}
^{237}Np 6.6x10^{-7}	^{232}U 1.1x10^{-6}	^{226}Ra 6.3x10^{-10}

Table IV. Isotopic composition of the siezed uranium %w/w (LLNL, 2001) as the basis for Scenario 7..

Isotope	**^{238}U**	**^{236}U**	**^{235}U**	**^{234}U**	**^{233}U**	**^{232}U**
w/w % of U	1.39E+01	1.19E+01	7.27E+01	1.10E+00	2.90E-05	1.10E-06
Mass of sample g	10	10	10	10	10	10
Isotope mass	1.39E+00	1.19E+00	7.27E+00	1.10E-01	2.90E-06	1.10E-07
Specific activity Bq/g	1.20E+04	2.40E+06	8.00E+04	2.30E+08	3.60E+08	7.90E+11
Sample activity Bq	1.67E+04	2.86E+06	5.82E+05	2.53E+7	1.04E+3	7.89E+4

Table V. Isotopic composition of the uranium of Scenario 7.

	Bq		Bq		Bq		Bq		Bq		Bq
^{238}U	1.67E+4	^{236}U	2.86E+6	^{235}U	5.82E+5	^{234}U	2.53E+7	^{233}U	1.04E+3	^{232}U	7.89E+4
^{234}Th	1.67E+4	^{232}Th	1.41E-3	^{231}Th	5.82E+5	^{230}Th	2.28E+3	^{229}Th	9.85E-1	^{228}Th	7.87E+4
^{234m}Pa	1.66E+4	^{228}Ra	5.92E-4	^{231}Pa	1.23E+2	^{226}Ra	4.93E+0	^{225}Ra	9.80E-1	^{224}Ra	7.87E+4
^{234}Pa	5.50E+1	^{228}Ac	5.92E-4	^{227}Ac	1.76E+1	^{222}Rn	4.91E+0	^{225}Ac	9.76E-1	^{220}Rn	7.87E+4
^{234}U	4.69E-1	^{228}Th	3.72E-4	^{227}Th	1.71E+1	^{218}Po	4.91E+0	^{221}Fr	9.76E-1	^{216}Po	7.87E+4
^{230}Th	2.09E-5	^{224}Ra	3.71E-4	^{223}Fr	2.43E-1	^{214}Pb	4.91E+0	^{217}At	9.76E-1	^{212}Pb	7.87E+4
^{226}Ra	2.99E-8	^{220}Rn	3.71E-4	^{223}Ra	1.72E+1	^{218}At	9.82E-4	^{213}Bi	9.76E-1	^{212}Bi	7.87E+4
^{222}Rn	2.98E-8	^{216}Po	3.71E-4	^{219}Rn	1.72E+1	^{214}Bi	4.91E+0	^{213}Po	9.55E-1	^{212}Po	5.04E+4
^{218}Po	2.98E-8	^{212}Pb	3.71E-4	^{215}Po	1.72E+1	^{214}Po	4.91E+0	^{209}Tl	2.11E-2	^{208}Tl	2.83E+4
^{214}Pb	2.98E-8	^{212}Bi	3.71E-4	^{211}Pb	1.72E+1	^{210}Pb	4.71E-1	^{209}Pb	9.76E-1		
^{218}At	5.95E-12	^{212}Po	2.38E-4	^{211}Bi	1.72E+1	^{210}Bi	4.68E-1				
^{214}Bi	2.98E-8	^{208}Tl	1.33E-4	^{207}Tl	1.72E+1	^{210}Po	4.01E-1				
^{214}Po	2.98E-8			^{211}Po	4.82E-2						
^{210}Pb	2.16E-9										
^{210}Bi	2.15E-9										
^{210}Po	1.76E-9										

Table VI. Isotopes and activities of the radionuclides in the source of Scenario 7. Shaded isotopes are those included.

The density of uranium oxide was taken to be 10.96 g/cm^3, the volume of the sample presented to the detector being 0.912 cm^3, this being presented in the form of a compact disc 2 cm in diameter and 2.9 mm in height. The detector was calibrated with an aqueous solution of equivalent geometry of the following nuclides: ^{241}Am – 30000 Bq, ^{57}Co – 10000 Bq, ^{60}Co – 10000 Bq, ^{54}Mn – 10000 Bq, ^{65}Zn – 10000, ^{88}Y – 10000 Bq, ^{137}Cs – 10000 Bq and ^{109}Cd – 10000 Bq and counted in the same configuration (ie. 10 cm above the detector). The composition of the uranium matrix was 11.85% w/w O and 88.15% w/w U. The sample was counted on a standard coaxial HPGe detector with a resolution of 1.8 keV at 1332 keV covering 10 to 3000 keV over 8k channels (0.36499 keV/channel). The calibration spectrum was provided such that participants could establish their own energy and shape calibration curve. Sufficient data was provided that the participants could derive a peak efficiency curve for the aqueous matrix although it is unlikely that such information would be of much use. Although the density of the material was provided, the extreme nature of that value (and the fact that it was primarily uranium) would most likely present severe difficulties in trying to correct the efficiency data. The mean free path length of sub-100 keV photons in such a matrix are significantly less than the thickness of the sample and this will present significant problems for a range of utilities commonly used for deriving density correction factors.

Significant complexity is also introduced due to the chemical composition of the matrix and it is doubtful whether such information could have been reproduced from the data provided.

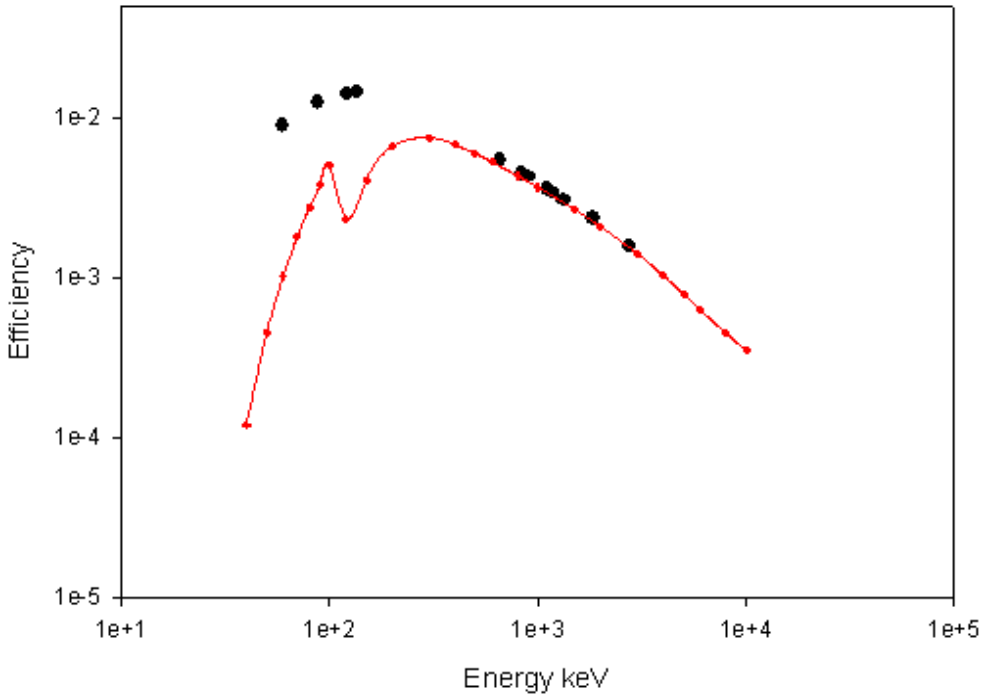


Figure 16. Difference between the efficiency data provided (black points) and the actual efficiency of the uranium sample for Scenario 7.

The accurate quantitative analysis of nuclear materials containing uranium at high levels is a specialized task and that is reflected in the number of published articles on the matter and the development of a number of specialized software tools for determining enrichment levels. The situation as presented in MALRAD could be considered somewhat realistic in that labs in many countries may not have experience in analyzing such materials and yet could theoretically find themselves in a position to have to attempt such an analysis with the instrumentation and staff to hand. In such a situation it could be reasonable to expect that an estimate could be made as to the nature of the material present, the enrichment level, the possible source of the material (fresh uranium, reprocessed etc) and an estimate of its age (since last purification). Although an extremely accurate analysis would necessitate procedures and instruments that may be beyond the capabilities of most national authorities or laboratories, it is possible to produce at least indicative estimates with the information to hand.

With respect to identification, although the number of peaks in the spectrum was large, the actual number of isotopes present was relatively small. The factor that could probably generate most problems in the analysis of such a spectrum is the fact that there are a large number of peaks present in the spectrum that are unlikely to appear in the isotope libraries of non-specialist laboratories due to their low emission probabilities and indeed a number of the isotopes present in the sample and of consequence are probably not present either. Although that should not actually hinder the analysis, misidentification of a host of peaks could theoretically lead to a wrong conclusion as to what the material actually consists of (nuclear waste, old fuel rods etc.).

For identification, the lower energy region of the spectrum is problematic given the large number of conflicting peaks from both gamma rays and x-rays. At energies above 150 keV the situation is less complex. The dominant signal of the spectrum is the 185.7 keV peak ^{235}U. The potential exists to misidentify it as ^{226}Ra but the total lack of the strong (and easily recognizable) daughter peaks from that isotope should have led most analysts to conclude it was the uranium isotope. Once the identification of ^{235}U was made, it should have been a logical conclusion that the material was enriched uranium of some kind especially given the lack of the usual ^{238}U series gamma signals that occur after ^{226}Ra. Two isotopes of consequence in deciding the nature of the material (i.e. that it was from reprocessed uranium as opposed to fresh) were ^{236}U and ^{232}U. Neither of these are simple isotopes for gamma spectrometry having weak emissions. The potential was present to identify ^{236}U but ^{232}U was essentially impossible using its own gammas. However ^{232}U has a suite of short lived daughters which were in equilibrium with the parent and the presence of these, clearly visible in the spectrum, should have been sufficient to alert analysts to the presence of the parent. The potential difficulty arises however in that many analysts may not be familiar with the decay chain of ^{232}U and assume that the isotopes such as ^{224}Ra, more commonly found as part of the ^{232}Th chain, had arisen from natural ^{232}Th thereby introducing an erroneous conclusion. The source of the ^{224}Ra and subsequent daughters sequence would however have been easily confimed had the analyst checked for the strong (and well known) emissions of the ^{228}Ac daughter of ^{232}Th which are not present in the ^{232}U sequence. Once ^{232}U had been identified in the sample, the analyst should have been in a position to conclude that the material was enriched uranium and that it had been produced from uranium that was previously in a reactor and had possibly been reprocessed using a gas diffusion process (as gas centrifuges exhibit little or sometimes no ^{232}U contamination). The knowledge that the material was processed

could probably lead to the logical hypothesis that ^{236}U was present and a confirmatory search should then have proved the matter. Once the material had been identified, the logical question would have been in relation to the level of enrichment and perhaps the age of the material, both requiring a quantitative estimate of activities (either absolute or relative to some isotope).

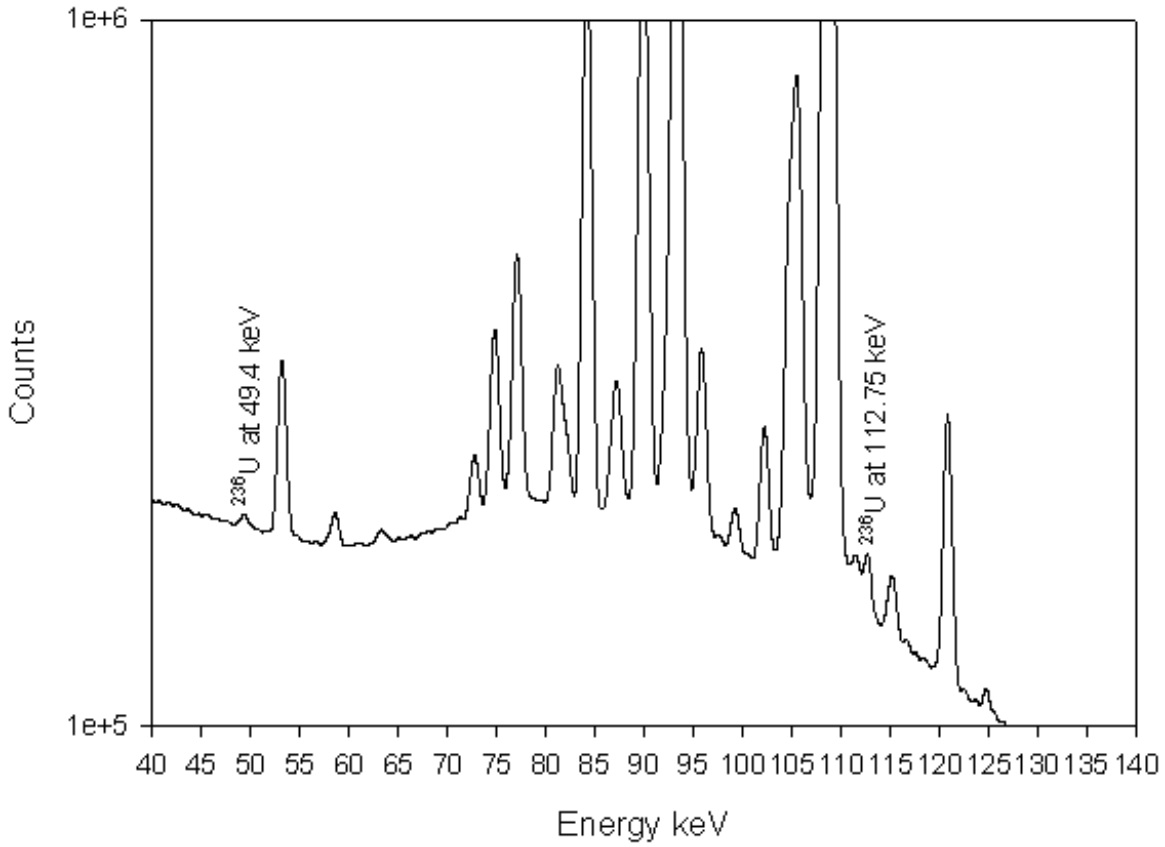


Figure 17. The 40 to 140 keV region of the Scenario 7 spectrum with the two ^{236}U peaks indicated.

For MALRAD the participants were provided with some rudimentary efficiency data such as one may consider reasonable to generate in a regular laboratory working with gamma spectrometry with materials to hand. This efficiency data deviates significantly from that of the actual sample due to the density and composition of the sample matrix. That is not to say however that such data is useless and it was hoped that the participants would have come up with solutions to the problem. A potential simple solution to at least some of the problems presented is provided by the presence of ^{208}Tl in the sample. The isolated position of the major peak of this isotope at the high energy end of the spectrum and its being a common feature of many environmental samples should have left most analysts in a position to identify

the isotope. Tl-208 exhibits a wide range of gamma energies between 211 keV and its main emission at 2614 keV, a number of which are relatively strong lines, and has a suite of x-rays between 72 and 87 keV. These gamma emissions could theoretically constitute a means of correcting the efficiency data supplied in Scenario 7 and facilitating a rudimentary correction of the efficiency curve, thereby allowing reasonable estimates to be made as to the activity of isotopes in the sample.

Using the calibration spectrum provided, the efficiency data was calculated and a standard efficiency plot drawn up. The following function was then fitted: log(Eff) = (-1.459E-4*E) – 2.496 + (2.653e+2/E) – (3.601e+4/E^2) + (1.994e+6/E^3) – (4.131e+7/E^4). Based on this function the efficiency at 2614 keV was calculated to be 0.00165558. It can be reasonably assumed that photons of this energy would be only slightly impacted upon by self absorption with the thin sample of Scenario 7 and to check, a simple tool (Gamatool®) was used to determine the absorption correction and this was determined to be of the order of 3%. Applying this factor provided a corrected value of 0.0016059126 for the efficiency of the sample at 2614 keV. A selection of the best (or simplest) resolved peaks of ^{208}Tl and their areas was then taken from the spectrum and based on an activity for ^{208}Tl calculated using the peak at 2614 keV and the modified efficiency value at that energy, the efficiency data for the individual peaks was calculated (See Table VII).

Energy keV	Peak area	Probability	Bq	Live time s	Efficiency
2614.00	910697	0.990000	28641	20000	0.001605913
1093.90	7595	0.004000	28641	20000	0.003314741
982.70	4238	0.002030	28641	20000	0.003644574
860.50	289676	0.124200	28641	20000	0.004071672
763.10	45962	0.018100	28641	20000	0.004433045
583.20	2595951	0.845000	28641	20000	0.005363171
277.40	275877	0.063100	28641	20000	0.007632520

Table VII. Derived efficiency values for Scenario 7. Activity value for ^{208}Tl being that derived from the peak area and corrected efficiency curve.

This provides efficiency data that can be assumed to be reasonably accurate over a useful energy range for the spectrum. A function of the form log(Eff) = -1.285E-4*E – 2.564 + 291.3/E – 4.372E+4/E^2 was then fitted to this data allowing for the derivation of efficiency data for points between 277 keV and 2614 keV. Based on this information it was then

possible to derive activity information for two isotopes which should facilitate determination of the enrichment level of the material; ^{235}U and ^{238}U via its daughter ^{234m}Pa.

Isotope	Energy keV	Area	Probability	Efficiency	Activity
^{235}U	279.5	235046	0.0027	0.00763225	570304
	345.4+345.9	92957	0.00108	0.00738633	582639
	368.5	57662	0.0007	0.00719759	572235
^{234m}Pa	766.4	4402	0.00294	0.00439716	17025

Table VII. Derived data for ^{235}U and ^{234m}Pa (and ^{238}U).

U-235 has a number of useful lines in the region for which efficiency data could be derived and using three of these an activity of 575059 Bq was determined. Although ^{234m}Pa has two useful lines, the more traditional 1001 keV peak was not used due to possible uncertainty in the emission probability and an activity of 17025 Bq for the isotope (and its parent ^{238}U) was derived based on the weaker but still useful line at 766.4 Bq. The relationship provided by Rucker and Johnson (1998):

$$\log mass\%\ ^{235}U = 1.065 - 0.7317\left(\log {}^{238}U/_{235}U\ activity\right) - 0.129\left(\log {}^{238}U/_{235}U\ activity\right)^2$$

was then used to estimate an enrichment value of 76.2% ^{235}U which is a reasonable approximation of the modeled value of the actual value of approximately 72% and would be sufficient to classify the material as weapons grade. Although a full treatment of uncertainties is not included in the above it would be possible to provide a conservative estimate of the uncertainty in the final enrichment value. It should be noted that the situation is made complex by the significant, but unknown, amount of ^{236}U present in the material. Alternatively it would be possible to derive an estimate of enrichment without having to assume a particular matrix correction factor for ^{208}Tl by simply by expressing ^{234m}Pa and ^{235}U relative to each other based on the efficiency "curve" provided by the ^{208}Tl peaks. Determining the time since last purification of the sample is a less straightforward matter as such a determination is normally achieved by utilizing the ratio between ^{234}U and ^{230}Th neither of which are easily amenable to determination by gamma spectrometry. U-234 has a useable line at 53 keV but this would be difficult in the extreme to utilize given the nature of the sample and the absence of any information as to efficiency in this region. A second useable line at 121 keV is again at a difficult position on the normal efficiency curve. Given the nature of the spectrum it is doubtful that the age of the sample could be determined with any accuracy by the majority of participants.

2.7.1. Reported Results.

Participant	Reported Data
1	The gamma spectrum of the sample shows the presence of uranium isotopes and daughters. Evaluation of the spectrum indicates uranium content in the sample of 50-60% (5-6 g of 10 g) and U enrichment ($^{235}U/^{235+238}U$) of 70-80%. Sample could be uranium oxide.
2	Participant withdrew
3	Participant withdrew
4	Presence of ^{235}U (3.35E+05 Bq), ^{224}Ra, ^{212}Pb, ^{208}Tl (2.6646E+04 Bq), ^{140}Ba, ^{239}Np, ^{109}Cd, ^{147}Nd, ^{234Th}, (2.1908E+03 Bq), ^{126}Sb, ^{227Th}, (5.2542E+02 Bq) ^{99m}Tc We can also claim that ^{239}Pu had no in-range peaks.
5	^{235}U
6	No data reported
7	The source is uranium-thorium mixture with the main isotopes ^{238}U, ^{235}U and ^{228}Th. Available calibration data allow us to measure activities of radionuclides in the sample aliquot of 10 g. Hence, we get the following activity concentration of ^{238}U, ^{235}U and ^{228}Th: 2.5 MBq/kg, 35 MBq/kg and 8.0 MBq/kg, respectively. Uncertainties are up to 30%. Thus, enrichment of uranium with the fissionable isotope ^{235}U is estimated by around 70%.
8	The spectrum and the density suggests that the fine brown powder is UO_2. It could have been UH_3 as well, but since UH_3 is pyroforic, we believe its not UH_3. Analysis of ^{235}U (185 keV) and ^{238}U (via ^{234m}Pa 1001 keV) gammalines suggests that the uranium is enriched. Our best guess is 70% enrichment, but it could be more due to the self-absorption of the 186 keV gamma.
9	Uranium, ^{235}U. The powder could be a kind of uranium concentrate.
10	Enriched uranium
11	^{232}Th, ^{228}Th (+ daughters), ^{235}U (+ ^{231}Th), ^{238}U (+ ^{234}Th, ^{234m}Pa); ^{228}Th, ^{232}Th - 25 kBq; ^{235}U - 300 kBq; ^{238}U - 20 kBq; Nuclear fuel, newly separated thorium + enriched uranium
12	The most pronounced nuclides are ^{224}Ra, ^{212}Pb, ^{212}Bi and ^{208}Tl. It could then be natural Thorium, but ^{228}Ac is missing in the spectrum. We therefore suppose that the identified nuclides are progeny of ^{232}U. It is a problem, though, that ^{208}Tl is too strong compared to ^{212}Pb and ^{212}Bi. The Genie software also suggests ^{226}Ra, but we discharge this nuclide since the spectrum does not contain ^{214}Bi or ^{214}Pb. The 186 keV peak is then most probably from ^{235}U. So we take a long shot and assume the source is reprocessed uranium after irradiation of fuel that contains ^{232}Th and highly enriched ^{235}U. The ^{232}U is then produced in the ^{233}U (n,2n)^{232}U reaction. The activity of ^{235}U is 0.3 MBq, and then the amount of ^{235}U is approximately 4 grams. If we base the evaluation of the amount of ^{232}U on the activity of ^{208}Tl of 1 MBq (having appr. 1/3 of the activity of ^{232}U) then the amount of ^{232}U is 4e-7 grams which is very low and indicates that the irradiation was short. However, assuming a thermal reactor neutron spectrum this should give an amount of ^{233}U in the order of 0.01 grams. To summarize we think the source is 4 grams of ^{235}U, 0.01 grams of ^{233}U and trace amounts of ^{232}U, $^{234}U$and ^{236}U.
13	A mixture of $^{235}U/^{238}U$ with daughters of ^{226}Ra serves visible. Enrichment ^{235}U 0.299%, ^{238}U 99.701%. Depleted Uranium. No artifical nuclides detected
14	The source is identified as HEU, around 80% ^{235}U in the form of UO_2. Traces of ^{232}U daughters and ^{236}U (from isotope correlation) in combination with high abundance of ^{234}U, suggests enrichment from reprocessed uranium.
15	No data reported
16	The presence of ^{208}Tl and other members of the Th decay series indicate that the sample contains ^{232}Th. The presence of ^{234}Pa, which is a decay product of ^{238}U, and the 185 keV peak from ^{235}U prove that uranium also is present.

17	The source is Uranium Dioxide UO_2 enriched 84.5 % in ^{235}U with ^{228}Th marker.The following radionuclides were found: ^{208}Tl, ^{212}Pb, ^{212}Bi, ^{224}Ra, ^{228}Th, ^{231}Pa, ^{234}Th, ^{234m}Pa, ^{234}U, ^{235}U, ^{238}U. Activity concentrations (Bq/kg, value ± 1 sigma counting unc.): ^{234}U 1.71E+09 ± 9.0E+06; ^{235}U 5.94E+07 ± 9.2E+03; ^{238}U 1.63E+06 ± 3.8E+04; ^{228}Th 1.01E+07 ± 2.0E+05. The weight abundance of uranium isotopes in 1 g and percentage: ^{234}U 0.0074 ± 0.0005 (0.84 %); ^{235}U 0.743 ± 0.003 (84.5 %); ^{238}U 0.129 ± 0.005 (14.7 %).
18	^{234m}Pa headed by ^{238}U is identified (chain stopped by ^{234}U and ^{230}Th). ^{235}U and ^{231}Th (chain stopped by ^{231}Pa). Thorium series detected from ^{228}Th down. Probably headed by ^{232}U. ^{233}U is indicated. It looks like reprocessed uranium. 235/238 atom ratio is about 2% if no correction for the attenuation is done. With that the ratio should be somewhat higher. Looks like reactor fuel uranium mixed with some other batch including ^{232}U that is reprocessed.

2.7.2 Discussion

As for Scenario 2, the spectrum of Scenario 7 provided the opportunity for deriving a lot of information from the material to hand. In general, participants appeared to have no trouble identifying the source as some kind of mixture of uranium isotopes with daughters present. In relation to the form of the material, the density value provided (being that of UO_2) was intended to be indicative of the sources form and it was hoped that, in combination with a correct identification and perhaps an estimate of activity and some stoichiometry, participants would have had enough information to identify the oxide and a number of participants did ascertain the correct identity. Discussions with some participants indicated that the software routine MGAU had been employed and provided results contrary to what the reporting analyst felt were reasonable and subsequently reported. It should be noted that the spectrum for Scenario 7 was simulated using a normal coaxial detector such as may be found in any laboratory. The MGAU code was originally developed for small volume (hence higher resolution) low energy gamma detectors. Such detectors display resolutions of 500 eV in the energy range that MGAU employs (80 to 120 keV) and this is significantly better than the 900 eV or so resolution of the detector for MALRAD. In addition, no attempt was made in the simulation to accurately and faithfully reproduce the differences in HPGe peak shapes that may occur for low energy gammas (Gaussian) and x-rays (Voight) or conduct a simulation directed at suitability for MGAU type assays. In this context, it could not be assured that the MALRAD scenarios would produce accurate results using MGAU (nor, for the same reasons, MGA with Scenario 2). The enrichment levels indicated by the participants ranged from 70% and upwards which were reasonable and would be sufficient to initiate the correct response. One participant produced isotope values of (weight per gram with actual values in parentheses) ^{234}U: 0.0074 ± 0.0005 (0.0011), ^{235}U: 0.743 ± 0.003 (0.727) and ^{238}U: 0.129 ± 0.005 (0.139) which were in good agreement with the actual data. Activities (Bq/kg) quoted

by the same participant, even for such a difficult sample were (reported data with actual in parentheses): ^{234}U 1.71E+09 ± 9.0E+06 (2.53E+09); ^{235}U 5.94E+07 ± 9.2E+03 (5.82E+07); ^{238}U 1.63E+06 ± 3.8E+04 (1.67E+06); ^{228}Th 1.01E+07 ± 2.0E+05 (7.87E+06) which were good results given the material to hand and the context of the scenario. A number of participants also recognized the fact that the uranium was reprocessed uranium as opposed to fresh. It was also quite satisfactory to note that some participants were able to elucidate that the common (for environmental samples) ^{208}Tl isotope was actually arising from ^{232}U as opposed to ^{232}Th. Reliance on "normal" commercial libraries for identifying the source was likely to produce erroneous results due to the profusion of peaks and the possible influence of such libraries on the analysis is reflected in a number of reported results. In general, it had been hoped by the organizers that more participants would have attempted quantitative analysis than actually did but it is probable that time constraints played a role in this aspect of the exercise.

3. Overall Conclusions and Recommendations.

Based on the results obtained from the participants and communications received, it appears that most participants have no significant problems in identifying single isotopes in uncomplicated situations even from spectra with low resolution. For the case of isotopes in the presence of shielding, especially when low energy lines are involved, the situation is a little different and the potential for difficulties were well demonstrated for Scenario 1. The scenarios that proved most difficult were those involving materials that participants were generally not familiar with – in particular Scenarios 2 and 7. While most participants were in a position to identify generally what the materials were (in relation to isotopes), there appeared to be either a general lack of a clear idea of what sort of information could or should be reported for such materials or an inability to derive that information. Such information includes the enrichment level and the type of uranium materials and the nature and age of plutonium materials. As the gamma spectrometric operations required to derive such information (to an accuracy level appropriate for first reponse) are standard, it should theoretically be within the grasp of most laboratories to provide such information. While it is accepted that international agencies have devoted significant efforts towards establishing state-of-the-art facilities and capacities in this area and would ultimately be called upon, a responsibility exists on the national level to be able to respond to such situations. At a minimum, such a national response should be able to establish whether or not international assistance is required and there are some indications that perhaps that is not the case. As an example, the interdiction of an amount of natural uranium mineral or even depleted uranium may not necessitate international assistance whereas highly enriched uranium probably would and it is therefore of some importance that, on a national level, the capacity exists to differentiate between such materials. In this respect it is possible that improvements could be gained in the general ability of laboratories to respond to incidents involving special nuclear materials both with respect to knowledge as to what information can be derived and how that information can be obtained from techniques such as gamma spectrometry. In relation to the Nordic and Baltic states it is possible that the most appropriate means of improving capacities in this regard is via approproiate seminars or exercises conducted under the auspices of bodies such as the NKS, the CBSS Working Group on Gamma Spectrometry or the NKS GammaSem network.

4. Bibliography.

Ancius, D., Ridikas, D., Remeikis, V., Plukis, A., Plukiene R.,Cometto, M:, 2005, Nukleonika 50(3), pp. 113−120

Agarwal, C., Poi, S., Nathaniel, T.N., Mhatre, A., Kalsi, P.C. Singh, S., Goswami, A., 2009, Journal of Nuclear Materials 385, pp. 131–133.

Dragnev, T. and Scharf, K., 1975, International Journal of Applied Radiation and Isotopes 26, 125.

Eckerman, K.F. and Sjoreen, A.L., 2006, Radiological Toolbox Users Manual, ORNL/TM-2004/27R1, Oak Ridge National Laboratory, P.O. Box 2008 Oak Ridge, Tennessee. P. 30.

Fetter, S. et al, 1990, Science & Global Security, 1 (3-4), pp. 225-302.

Fleissner, J.G., "GRPAUT: A Program for Pu Isotopic Analysis (A User's Guide)", Mound Laboratory Report MLM-2799 (January 1981).

Gunnink, R., "A New One-Detector Analysis Method for Rapid High-Precision Plutonium Isotopic Measurements", Proceedings of the 9th ESARDA Symposium on Safeguards and Nuclear Material Management, London,UK, 12-14 May 1987: 167-171.

Hensley, W. K., McKinnon, A. D., Miley, H. S., Panisko, M. E., Savard, R. M., 1995, Journal of Radioanalytical and Nuclear Chemistry, Volume 193, Number 2 / June, 1995, 229-237.

Hong, W., 2001, SPECON 2000 User Manual; Korea Institute of Geoscience and Mineral Resources (KIGAM).

Keegan, R.P., Gehrke, R.J., 2003, Applied Radiation and Isotopes 59, pp. 137–143.

Lawrence Livermore National Laboratory, Forensic Analysis of a Smuggled HEU Sample Interdicted in Bulgaria, , US Dept. of Energy, UCRL-ID-143216, 2001.

McGinnis, R., 2008, RadPro Calculator User Guide v. 3.23.

Mullen, Robert K., "Nuclear Violence", in Preventing Nuclear Terrorism: The Report and Papers of the International Task Force on Prevention of Nuclear Terrorism, ed. by Paul Leventhal and Yonah Alexander, 1987, Lexington, MA: Lexington Books, pp. 231-247.

Nature, "Researcher faces life in prison for revenge radiation poisoning," Nature, 2003. 425:552.

Peurrung, A., Arthur, R., Elovich, R., Geelhood, B., Kouzes, R., Pratt, S., Scheele, R., Sell, R., 2001, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 474/3, pp. 285-293.

Plenteda, R. 2002. A Monte Carlo Based Virtual Gamma Spectroscopy Laboratory. Ph.D. Thesis. Universitaetsbibliothek der Technischen Universitaet Wien, Resselgasse 4, A-

1040 Wien, Austria. 118 p.

Rucker, T. L. and Johnson, C. M., 1998, Journal of Radioanalytical and Nuclear Chemistry, Volume 235/1-2, pp.47-52.

Sampson, T.E., Hsue, S-T, Parker, J.L., Johnston, S.S., Bowersox, D.F., 1982, Nucl. Inst and Meth 193 pp. 177-183.

Sampson, T.E., 1986, Plutonium Isotopic Composition by Gamma-Ray Spectroscopy: A Review, Los Alamos National Laboratory report LA-10750-MS.

Sampson, T.E., Nelson, G.W., Kelly, T. A. "FRAM:A versatile Code for Analyzing the Isotopic Ratios of Plutonium from Gamma-Ray Pulse Height Spectra", LosAlamos National Laboratory Report LA-11720-MS, December 1989.

Sevan'kaev, A. V., D. C. Lloyd, A. A. Edwards, G. F. Mikhailova, V. Yu. Nugis, E. V. Domracheva, A. E. Baranov, A. A. Davtian, A. A. Gordeeva, I. A. Gusev, A. K. Guskova, V.V. Moiseenko, and Yu. V. Olshanskaya, 1999, Radiation Protection Dosimetry, 81, pp. 85-90.

Wallenius, M., Lutzenkirchen, K., Mayer, K., Ray, I., Aldave de las Heras, L.,Betti, M., Cromboom, O., Hild, M., Lynch, B., Nicholl, A., Ottmar, H., Rasmussen, G., Schubert, A., Tamborini, G., Thiele, H.,Wagner, W., Walker, C., Zuleger, E., 2007, Journal of Alloys and Compounds 444–445, pp. 57–62.

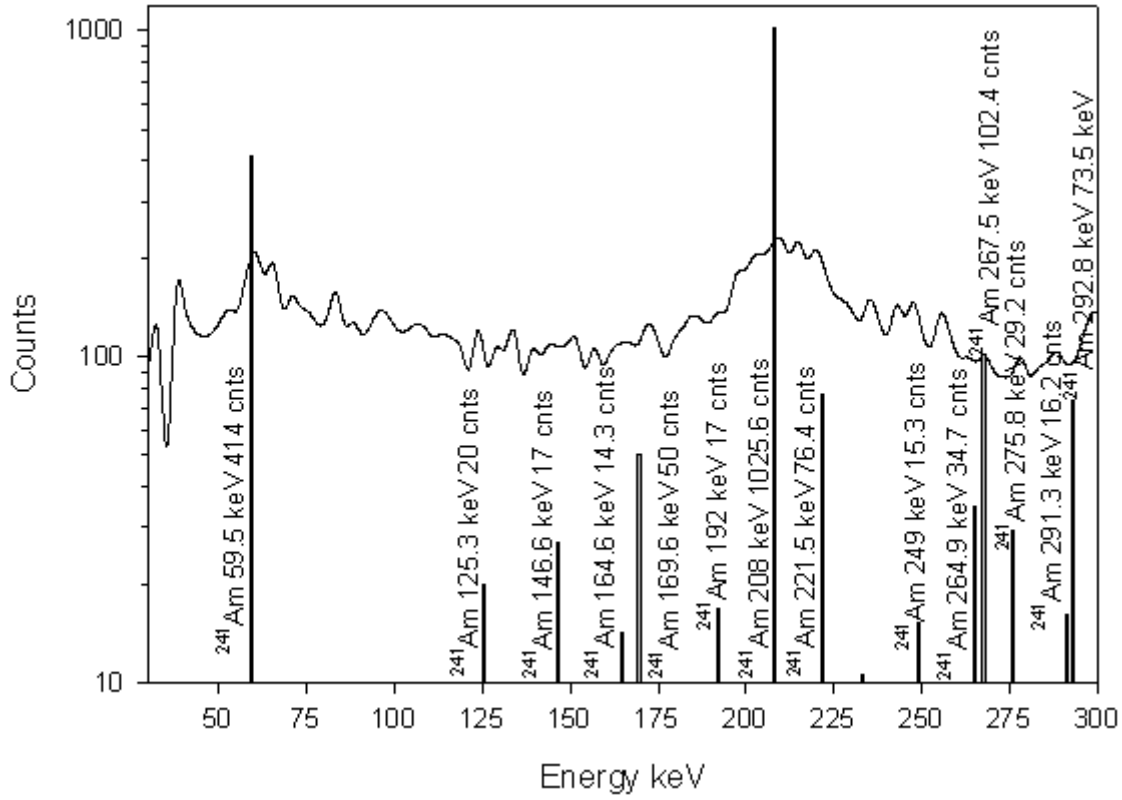
Wallenius, M., Mayer, K., 2000, Fresenius J Anal Chem, 366, pp. 234–238.

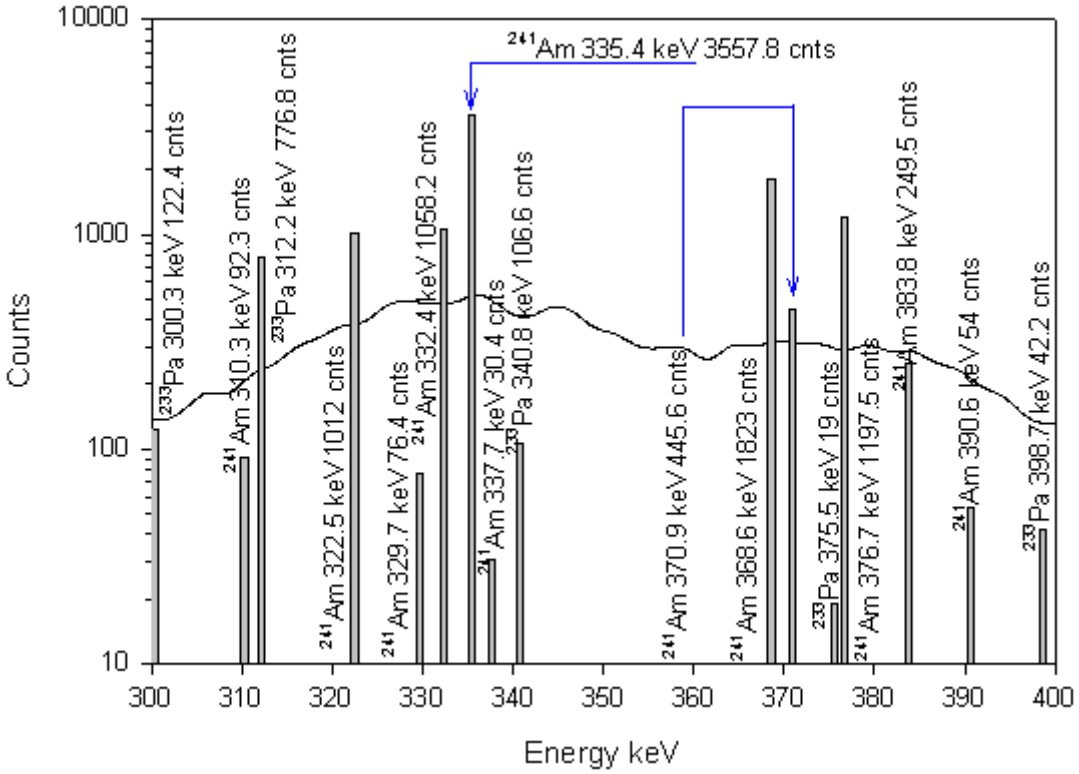
APPENDIX 1 – Spectral information for Scenario 1

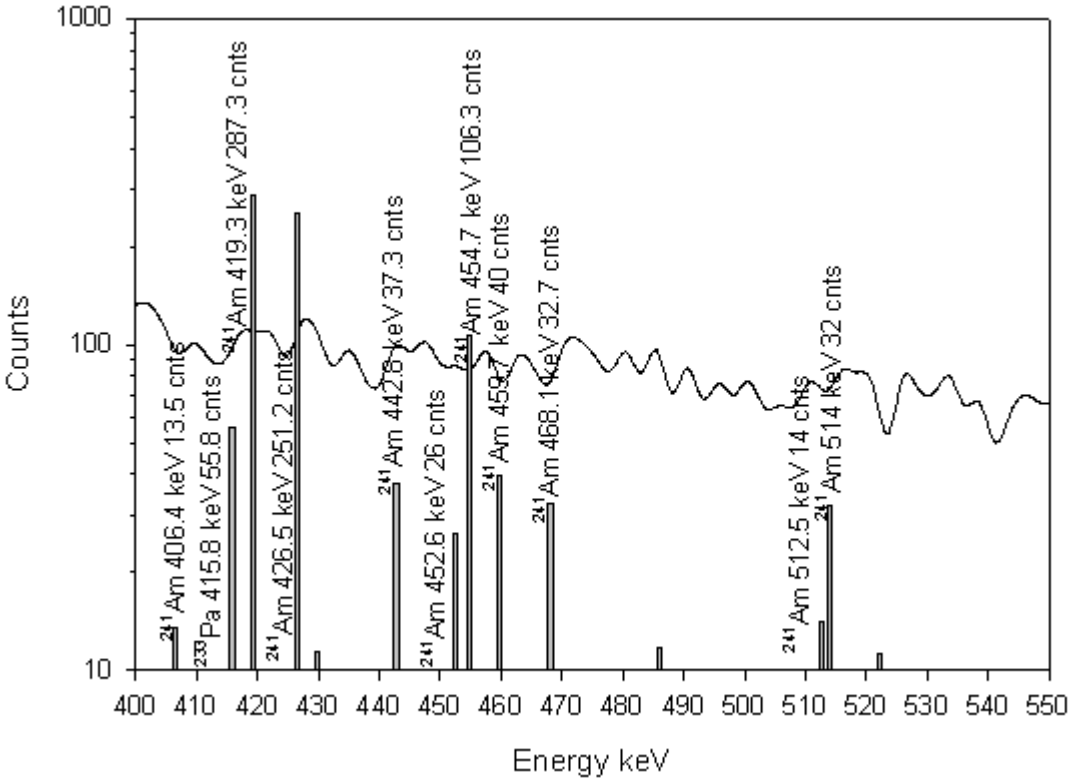
Nuclide	Energy keV	HPGe Channel	HPGe Counts	HPGe FWHM keV	NaI Channel	NaI Counts	NaI FWHM keV
^{241}Am	59.5	157	96.6	0.9	20	414.5	10.27
^{241}Am	125.3	365	9.3	0.9	46	20	16.3
^{241}Am	146.6	432	13	0.9	54	26.9	17.96
^{241}Am	150	443	2.8	0.9	55	5.8	18.22
^{241}Am	164.6	489	7	0.9	61	14.3	19.3
^{241}Am	165.8	493	2.6	0.9	62	5.4	19.39
^{241}Am	169.6	505	24.3	0.9	63	50	19.66
^{241}Am	175.1	522	3.3	0.9	65	6.9	20.05
^{241}Am	192	576	8.1	0.9	72	16.9	21.23
^{241}Am	208	626	477.1	0.9	78	1025.6	22.31
^{241}Am	221.5	669	34.7	0.9	84	76.4	23.2
^{241}Am	232.9	705	4.7	0.9	88	10.6	23.93
^{241}Am	246.7	749	3.1	0.9	94	7.1	24.8
^{241}Am	249	756	6.6	0.9	94	15.3	24.95
^{241}Am	264.9	806	14.6	0.9	101	34.7	25.92
^{241}Am	267.5	815	42.8	0.9	102	102.4	26.08
^{241}Am	275.8	841	12	0.9	105	29.2	26.58
^{241}Am	291.3	890	6.5	0.9	111	16.2	27.49
^{241}Am	292.8	894	29.3	0.9	112	73.5	27.58
^{233}Pa	300.3	918	48.2	0.9	115	122.4	28.02
^{241}Am	304.2	931	2.3	0.91	116	5.9	28.24
^{241}Am	310.3	950	36.4	0.92	119	92.3	28.59
^{233}Pa	312.2	956	306.1	0.92	119	776.8	28.7
^{241}Am	322.5	988	398.7	0.94	124	1012.2	29.29
^{241}Am	329.7	1011	30.1	0.95	126	76.4	29.69
^{241}Am	332.4	1020	416.7	0.95	127	1058.2	29.84
^{241}Am	335.4	1029	1400.9	0.95	129	3557.8	30
^{241}Am	337.7	1037	12	0.96	130	30.4	30.13
^{233}Pa	340.8	1046	42	0.96	131	106.6	30.3
^{241}Am	349.5	1074	3.6	0.97	134	9.3	30.78
^{241}Am	358.3	1101	3.8	0.99	138	9.6	31.26
^{241}Am	368.6	1134	716.2	1	142	1822.8	31.81
^{241}Am	370.9	1142	175.1	1	143	445.6	31.94
^{233}Pa	375.5	1156	7.4	1.01	144	18.9	32.18
^{241}Am	376.7	1160	470.2	1.01	145	1197.5	32.24
^{241}Am	383.8	1182	97.9	1.02	148	249.5	32.62
^{241}Am	390.6	1204	21.1	1.03	150	53.9	32.98
^{233}Pa	398.7	1229	16.5	1.04	154	42.2	33.4
^{241}Am	406.4	1254	5.3	1.05	157	13.5	33.8
^{233}Pa	415.8	1283	21.9	1.06	160	55.8	34.28
^{241}Am	419.3	1295	112.5	1.07	162	287.3	34.46
^{241}Am	426.5	1317	98.4	1.08	165	251.2	34.82
^{241}Am	429.9	1328	4.5	1.08	166	11.5	35
^{241}Am	442.8	1369	14.6	1.1	171	37.3	35.65
^{241}Am	452.6	1400	10.2	1.11	175	26.2	36.13
^{241}Am	454.7	1406	41.6	1.11	176	106.3	36.23
^{241}Am	459.7	1422	15.6	1.12	178	39.9	36.48
^{241}Am	468.1	1449	12.8	1.13	181	32.7	36.9
^{241}Am	485.9	1505	4.6	1.15	188	11.7	37.76
^{241}Am	512.5	1589	5.5	1.18	199	14.1	39.03
^{241}Am	514	1594	12.5	1.18	199	32	39.1
^{241}Am	522.1	1620	4.4	1.19	202	11.2	39.48
^{241}Am	573.9	1784	6.3	1.25	223	16.1	41.87

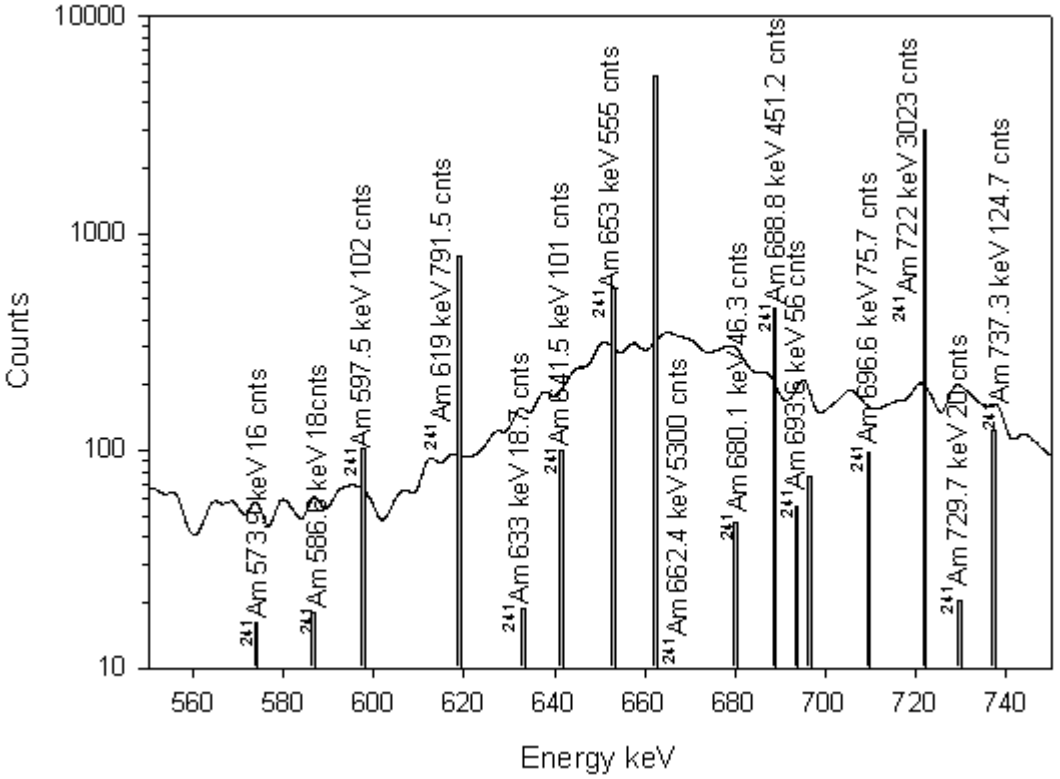
^{241}Am	586.6	1824	7	1.26	228	17.9	42.43
^{241}Am	597.5	1858	40.1	1.27	232	102.2	42.92
^{241}Am	619	1926	311.2	1.3	241	791.5	43.87
^{241}Am	627.2	1952	3.1	1.3	244	8	44.23
^{241}Am	633	1971	7.3	1.31	246	18.7	44.49
^{241}Am	641.5	1997	39.8	1.32	250	101.1	44.85
^{241}Am	653	2034	218.8	1.33	254	555	45.35
^{241}Am	662.4	2064	2091.6	1.34	258	5300.5	45.76
^{241}Am	669.8	2087	2.2	1.35	261	5.6	46.07
^{241}Am	676	2107	3.8	1.35	263	9.6	46.34
^{241}Am	680.1	2119	18.3	1.36	265	46.3	46.51
^{241}Am	688.8	2147	178.5	1.37	268	451.2	46.88
^{241}Am	693.6	2162	22.1	1.37	270	55.9	47.08
^{241}Am	696.6	2172	29.9	1.37	271	75.7	47.21
^{241}Am	709.5	2212	38.8	1.39	277	97.9	47.75
^{241}Am	722	2252	1199	1.4	282	3023	48.27
^{241}Am	729.7	2276	8	1.41	285	20.2	48.59
^{241}Am	731.5	2282	2.9	1.41	285	7.3	48.66
^{241}Am	737.3	2300	49.5	1.41	288	124.7	48.9
^{241}Am	755.9	2359	47.7	1.43	295	120	49.66
^{241}Am	759.5	2371	10.7	1.44	296	26.9	49.8
^{241}Am	767	2394	31.6	1.44	299	79.4	50.11
^{241}Am	770.5	2405	31.7	1.45	301	79.6	50.25
^{241}Am	772.4	2411	16.9	1.45	301	42.4	50.33
^{241}Am	789.2	2464	2.5	1.46	308	6.3	51
^{241}Am	801.9	2505	8.4	1.47	313	21.1	51.51
^{241}Am	812	2537	3.9	1.48	317	9.8	51.91
^{241}Am	819.3	2560	2.6	1.49	320	6.6	52.2
^{241}Am	851.6	2662	2.5	1.52	333	6.3	53.47
^{241}Am	862.7	2697	3.5	1.53	337	8.8	53.9
^{241}Am	872.7	2729	4.7	1.54	341	11.8	54.29
^{241}Am	902.5	2823	2.1	1.56	353	5.1	55.43
^{241}Am	955.7	2991	4.1	1.61	374	10.1	57.43

Table A1. Comparison of the characteristics of constituent photopeaks for the simulations of scenario 1 for both the NaI and HPGe detectors.


Counts
Energy keV
1000
100
10
50
75
100
125
150
175
200
225
250
275
300
241Am 59.5 keV 414 cnts
241Am 125.3 keV 20 cnts
241Am 146.6 keV 17 cnts
241Am 164.6 keV 14.3 cnts
241Am 169.6 keV 50 cnts
241Am 192 keV 17 cnts
241Am 208 keV 1025.6 cnts
241Am 221.5 keV 76.4 cnts
241Am 249 keV 15.3 cnts
241Am 264.9 keV 34.7 cnts
241Am 267.5 keV 102.4 cnts
241Am 275.8 keV 29.2 cnts
241Am 291.3 keV 16.2 cnts
241Am 292.8 keV 73.5 keV


Counts
Energy keV
10000
1000
100
10
300
310
320
330
340
350
360
370
380
390
400
241Am 335.4 keV 3557.8 cnts
233Pa 300.3 keV 122.4 cnts
241Am 310.3 keV 92.3 cnts
233Pa 312.2 keV 776.8 cnts
241Am 322.5 keV 1012 cnts
241Am 329.7 keV 76.4 cnts
241Am 332.4 keV 1058.2 cnts
241Am 337.7 keV 30.4 cnts
233Pa 340.8 keV 106.6 cnts
241Am 370.9 keV 445.6 cnts
241Am 368.6 keV 1823 cnts
233Pa 375.5 keV 19 cnts
241Am 376.7 keV 1197.5 cnts
241Am 383.8 keV 249.5 cnts
241Am 390.6 keV 54 cnts
233Pa 398.7 keV 42.2 cnts


Counts
Energy keV
1000
100
10
400 410 420 430 440 450 460 470 480 490 500 510 520 530 540 550
241Am 406.4 keV 13.5 cnts
233Pa 415.8 keV 55.8 cnts
241Am 419.3 keV 287.3 cnts
241Am 426.5 keV 251.2 cnts
241Am 452.6 keV 26 cnts
241Am 454.7 keV 106.3 cnts
241Am 459.7 keV 40 cnts
241Am 468.1 keV 32.7 cnts
241Am 512.5 keV 14 cnts
241Am 514 keV 32 cnts


Counts
Energy keV
10000
1000
100
10
560 580 600 620 640 660 680 700 720 740
241Am 573.9 keV 16 cnts
241Am 586.2 keV 18cnts
241Am 597.5 keV 102 cnts
241Am 619 keV 791.5 cnts
241Am 633 keV 18.7 cnts
241Am 641.5 keV 101 cnts
241Am 653 keV 555 cnts
241Am 662.4 keV 5300 cnts
241Am 680.1 keV 46.3 cnts
241Am 688.8 keV 451.2 cnts
241Am 696.6 keV 75.7 cnts
241Am 722 keV 3023 cnts
241Am 729.7 keV 20 cnts
241Am 737.3 keV 124.7 cnts

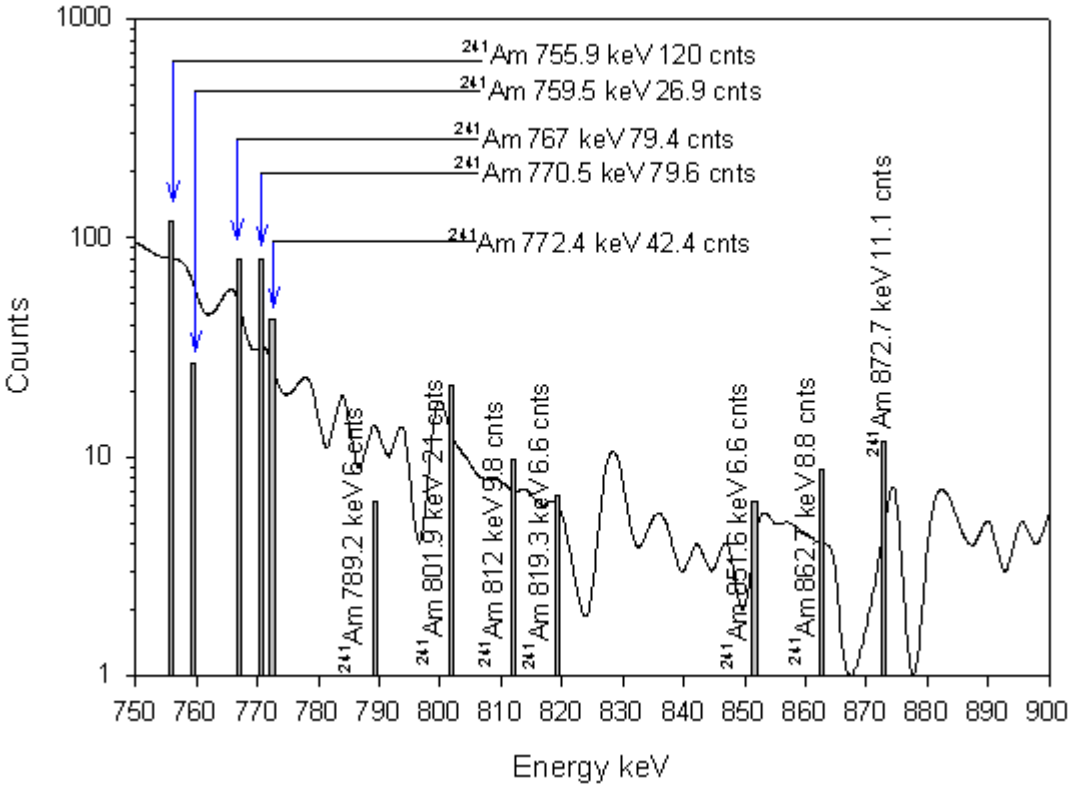


Figure A1. Assignation of constituent peaks in the spectrum of Scenario 1.

APPENDIX 2 – Spectral information for Scenario 2.

Nuclide	Channel	Energy	Counts
Pu-239	171	51.6	7.8
Am-241	188	55.6	12.8
Pu-239	193	56.8	10.3
Am-241	197	57.9	13.2
U-237	204	59.5	65.1
Am-241	204	59.5	209330.5
Am-241	226	64.8	6.7
U-237	226	64.8	19.9
Pu-239	229	65.7	18.2
Am-241	237	67.5	48.7
Pu-239	237	67.7	119.6
Pu-239	242	68.7	293
Pu-239	242	68.7	108.3
Am-241	246	69.8	608.6
Pu-241	254	71.6	12.3
Pu-239	267	75	164.4
Pa-233	269	75.3	5.1
Am-241	271	75.8	91.3
Pu-241	276	77.1	294.5
Pu-239	278	77.6	3065.4

Pu-239	282	78.4	1173.1
Th-231	305	84.2	3.3
Np-237	315	86.5	269.8
Pa-233	316	86.8	44.4
Np-237	321	88	3.7
Pu-239	327	89.4	78.1
Pu-239	328	89.6	1206.5
U-235	329	90	6.2
Np-237	339	92.3	67.2
U-235	343	93.4	16.2
Pa-233	348	94.7	577.1
Pu-240	348	94.7	402
Pu-241	348	94.7	24515.6
Pu-239	348	94.7	248664.5
Pu-238	348	94.7	61.7
Np-237	349	94.7	32.2
Np-237	353	95.9	160.4
Am-241	358	97.1	17181.6
U-237	358	97.1	72399.9
Pu-239	364	98.4	543673.8
Pu-238	364	98.4	140.5
Pa-233	364	98.4	1316.5
Pu-241	364	98.4	60907.5
Pu-240	364	98.4	916.9
Pu-239	365	98.8	119850.6
Am-241	366	99	327261.2
Pu-238	370	99.9	9515.1
U-237	375	101.1	162020.5
Am-241	375	101.1	229267
U-237	383	103	45.8
Am-241	383	103	431616
Pu-239	383	103	31648.1
Pu-242	385	103.5	11.7
Pu-241	386	103.7	31235.7
Pa-233	387	104	100.5
Pu-240	388	104.2	249371.9
U-235	390	104.8	5
U-235	394	105.6	9.8
Np-237	396	106.1	7.2
Np-237	405	108.4	97.8
U-235	406	108.6	44.7
Np-237	406	108.7	10.9
U-235	407	109	16.8
U-235	408	109.2	7.9
Am-241	410	109.7	171.4
Pu-240	413	110.4	268
Pu-241	416	111	79946.8
Pu-239	416	111	528233.7
Pa-233	417	111.3	769
Pu-240	417	111.3	537.2
Pu-238	417	111.3	82
Np-237	419	111.9	60.9
Pu-240	420	112	20.6
Am-241	425	113.3	64970.4
U-237	428	113.9	139284.8
Pu-241	428	114	3620.5
Pu-238	430	114.4	37.9
Pu-240	430	114.4	248
Pu-241	430	114.4	15215.2
Pu-239	430	114.4	148684.5

Pu-240	432	114.8	90.5
Pu-241	432	114.8	5598.1
Pa-233	432	114.9	464.5
Pu-239	432	114.9	52664
Pu-239	434	115.4	138324.9
Pu-239	437	116.3	187967.8
Np-237	443	117.7	43.2
U-237	444	117.9	58288.9
Am-241	444	117.9	138.3
Pu-239	452	119.7	8258.7
Pu-239	452	119.7	3759.5
U-234	457	120.9	12.9
Pu-241	458	121.2	592.9
Pu-239	462	122.4	332.2
Am-241	465	123	18421.1
Pu-239	468	123.6	2312.7
Pu-239	471	124.5	7481.1
Pu-239	474	125.2	8939.8
Am-241	475	125.3	81565.2
Pu-239	491	129.3	942830.5
Np-237	498	131.1	10.8
Np-237	512	134.3	9.5
Pu-239	542	141.7	7441.9
Np-237	549	143.2	83
Pu-239	550	143.7	4287.2
U-235	551	143.8	67.1
Pu-239	552	144.2	71276.6
Pu-239	560	146.1	31726.1
Am-241	562	146.6	20080.1
Pu-241	570	148.5	111626.8
Am-241	576	150	3570.6
Np-237	582	151.4	58.5
Pu-238	588	152.7	3630.2
Am-241	594	154.3	27
Np-237	598	155.2	24.9
Pu-239	611	158.4	371.3
Am-241	614	159.3	85.8
Pu-241	617	160	5372.8
Pu-239	618	160.2	2406.4
Pu-240	619	160.3	38335.8
Pu-239	623	161.5	49198.1
Am-241	624	161.5	97.1
Np-237	628	162.5	10.4
U-235	631	163.4	52.3
Am-241	636	164.6	4578.9
U-237	636	164.6	41794.1
Am-241	641	165.8	1655.8
Pu-239	650	167.8	1338.8
Np-237	655	169.2	27.4
Am-241	657	169.6	13388.8
Np-237	661	170.6	7.7
Pu-239	664	171.4	55253.4
Pu-239	674	173.7	1617.4
Am-241	680	175.1	1558.8
Np-237	684	176.1	7.8
Pu-239	697	179.2	38291.3
Np-237	703	180.8	10.7
U-235	710	182.5	5.2
Pu-239	719	184.6	1341.6
U-235	723	185.7	919.3

Pu-239	733	188.1	7401.4
Pu-239	738	189.3	57553.7
Am-241	743	190.4	250.9
Np-237	747	191.5	14.2
Am-241	749	192	2524.1
Np-237	755	193.3	30
U-235	761	194.9	11.8
Np-237	761	195	110.2
Pu-239	764	195.7	82082.2
Pu-239	769	196.9	2890.8
Np-237	769	196.9	12.3
Am-241	770	197	62
U-235	781	199.6	2
Np-237	782	200	2.6
Pu-238	786	201	39
Am-241	789	201.7	135.1
Np-237	789	201.7	28
Np-237	790	202	3.2
U-235	791	202.1	22.4
Pu-239	797	203.5	487881.2
Am-241	799	204.1	404.3
U-235	804	205.3	108.2
U-237	815	208	1004261
Am-241	815	208	115443.5
Np-237	820	209.2	11.3
Np-237	833	212.3	116.8
Pu-240	833	212.5	6728.1
Np-237	840	214	34.6
Pu-239	856	218	1222.6
U-235	870	221.4	3.1
Am-241	870	221.5	7173.4
U-237	872	221.8	1175.8
Pu-239	887	225.4	16649.5
Np-237	906	230	12
Am-241	917	232.9	883
Am-241	924	234.4	136.1
U-237	924	234.4	1290.8
Pu-238	925	234.6	2.9
Pu-239	938	237.8	17912.8
Th-231	938	237.8	2.8
Np-237	938	237.9	62
U-235	950	240.9	2.4
Pu-239	955	242.1	9443.2
Am-241	957	242.4	6.3
Pu-239	961	243.4	33106.9
Pu-239	967	244.9	6762.4
Am-241	967	245	6.4
Am-241	975	246.7	522.3
Pa-233	982	248.5	63.3
Pu-239	983	248.9	10290.9
Np-237	983	248.9	5.2
Am-241	984	249	1109.5
Pu-239	1010	255.4	115757.1
Np-237	1017	257.1	7.4
Pa-233	1023	258.5	4.5
Am-241	1033	260.9	244
Np-237	1039	262.4	8.1
Pu-239	1045	263.9	40972.8
Am-241	1049	264.9	2263.7
Pu-239	1053	265.8	4704

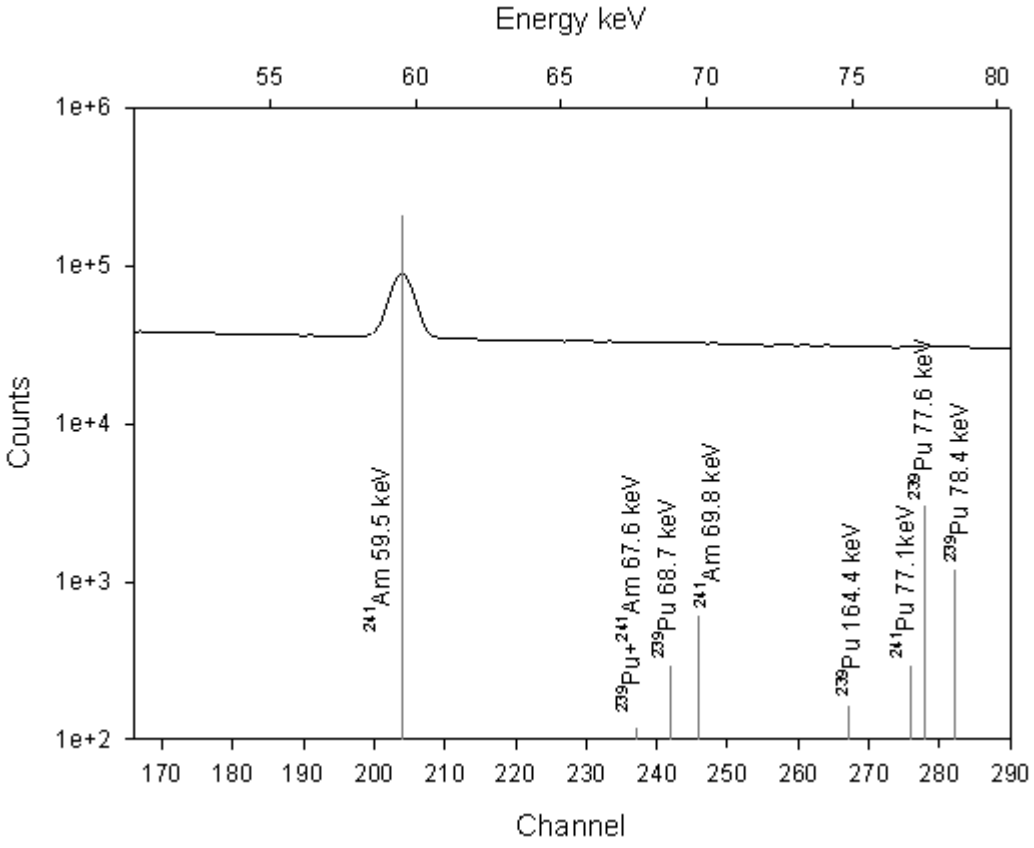
Am-241	1060	267.5	6574.4
U-237	1060	267.5	59048.3
Am-241	1073	270.6	168.4
Pa-233	1076	271.5	364.3
Am-241	1094	275.8	1794.7
U-235	1109	279.5	11.5
Np-237	1110	279.6	2.3
Pu-239	1116	281.1	3664.5
Pu-239	1133	285.3	3407.9
Am-241	1158	291.3	930.9
U-237	1164	292.8	245.4
Am-241	1164	292.8	4190.5
Pu-239	1183	297.5	96252.8
Pa-233	1189	298.9	53.5
Am-241	1194	300.1	31.7
Pa-233	1195	300.3	10201.8
Pu-239	1206	302.9	10167.3
Am-241	1211	304.2	325.2
Pu-239	1226	307.8	11272.2
Am-241	1236	310.3	5034
Pu-239	1242	311.7	54030.5
Pa-233	1244	312.2	63527.4
Pu-239	1261	316.4	28337.3
Pu-239	1275	319.8	10483.5
Pu-239	1280	320.9	119024.8
Am-241	1287	322.5	54370.4
Pu-239	1292	323.9	120195.5
Am-241	1316	329.7	4075
U-237	1327	332.4	145599.5
Am-241	1327	332.4	56279
Pu-239	1329	332.8	1149836
Am-241	1339	335.4	188746.5
U-237	1339	335.4	11700.5
Pu-239	1342	336.1	264673.2
Am-241	1349	337.7	1610.2
U-237	1349	337.7	1106.9
Pa-233	1362	340.8	8460.5
Pu-239	1365	341.5	160271
Pu-239	1379	345	1367088
U-235	1381	345.4	4.2
U-235	1383	345.9	2.3
Am-241	1397	349.5	485.8
Pu-239	1416	354	1788
Am-241	1434	358.3	503.6
Pu-239	1448	361.8	30819.4
Pu-239	1470	367.1	239192.3
U-235	1476	368.5	4.7
Pu-239	1476	368.5	242117.3
Am-241	1476	368.6	94746.5
U-237	1476	368.6	5534.8
Am-241	1486	370.9	23145.5
U-237	1486	370.9	15286.2
Pu-239	1503	375	4300695
Pa-233	1504	375.5	1474.8
Am-241	1509	376.7	62035.7
Pu-239	1524	380.2	859302.8
Pu-239	1534	382.8	736193.9
Am-241	1539	383.8	12900.7
U-235	1556	387.9	2.7
U-235	1566	390.3	2.9

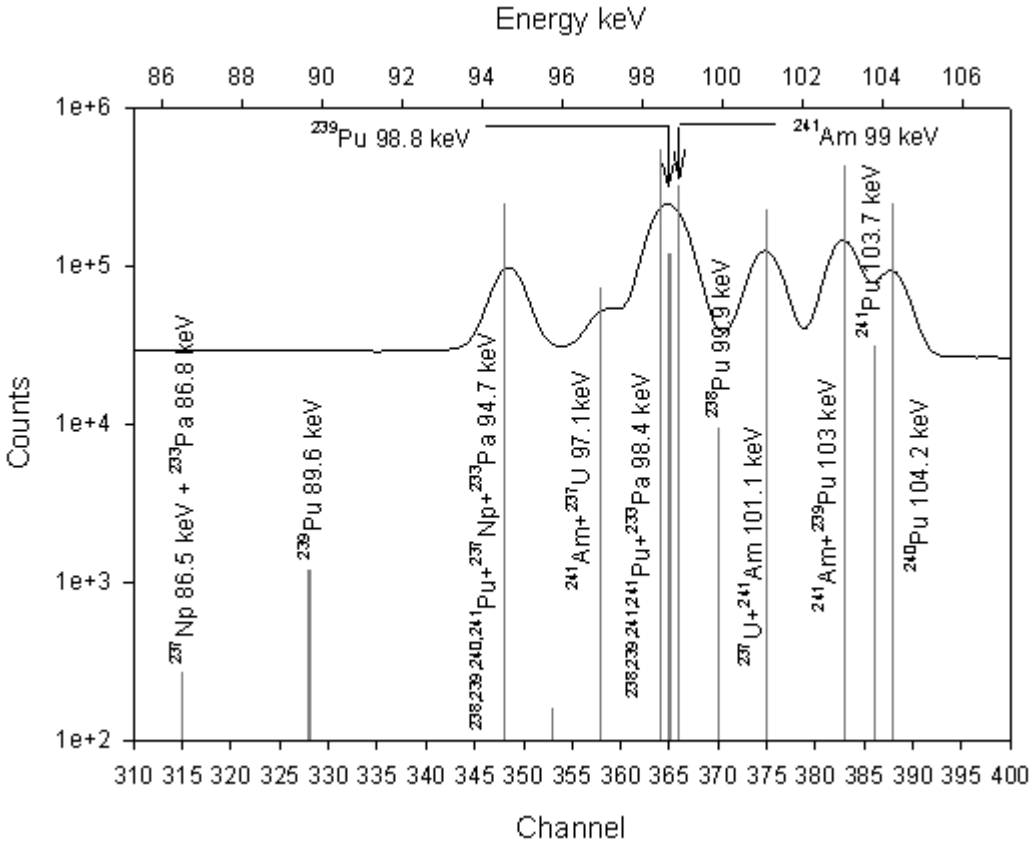
Am-241	1567	390.6	2779.9
Pu-239	1575	392.6	601740.6
Pu-239	1577	393.1	1029288
Pa-233	1600	398.7	3261.1
Pu-239	1604	399.5	17699.1
Am-241	1632	406.4	691.2
Pu-239	1634	406.9	7664.4
Pu-239	1651	411	21718
Pu-239	1657	412.4	56.1
Pu-239	1662	413.7	4562657
Pa-233	1670	415.8	4299.8
Am-241	1685	419.3	14711.5
Pu-239	1698	422.6	380831
Am-241	1714	426.5	12845.8
Pu-239	1715	426.6	74069.6
Am-241	1729	429.9	587.3
Pu-239	1730	430.2	14030.5
Am-241	1782	442.8	1899.1
Pu-239	1794	445.7	29788.1
Pu-239	1798	446.8	2849.9
Pu-239	1817	451.5	647715.4
Am-241	1822	452.6	1331.7
Am-241	1831	454.7	5407.3
Pu-239	1843	457.7	5173.7
Am-241	1851	459.7	2027.6
Pu-239	1858	461.2	6994.3
Pu-239	1868	463.7	984
Am-241	1886	468.1	1659.8
Pu-239	1911	474.3	322.8
Pu-239	1941	481.5	16706.7
Am-241	1959	485.9	592.3
Pu-239	1964	487	953.1
Pu-239	1989	493.1	3221.3
Am-241	2069	512.5	709.2
Am-241	2075	514	1603
Am-241	2108	522.1	561.4
Pu-240	2174	538.1	135.8
Pu-239	2177	538.9	1182.6
Pu-239	2225	550.5	1677.1
Am-241	2322	573.9	791.8
Am-241	2357	582.6	151.6
Pu-239	2372	586.1	631.4
Am-241	2374	586.6	873.8
Am-241	2418	597.5	4975.7
Pu-239	2421	598.1	7165.6
Pu-239	2427	599.6	834.1
Pu-239	2457	606.9	503.1
Pu-239	2482	612.8	3998.8
Pu-239	2499	617.1	5655.5
Pu-239	2504	618.3	8616.9
Am-241	2507	619	38215.1
Pu-239	2508	619.3	5113.3
Pu-239	2531	624.8	1853
Am-241	2541	627.2	382.7
Am-241	2565	633	896
Pu-239	2565	633.1	10779.3
Pu-239	2584	637.7	10679
Pu-239	2593	640	37201.9
Am-241	2599	641.5	4841
Pu-240	2603	642.3	13051.8

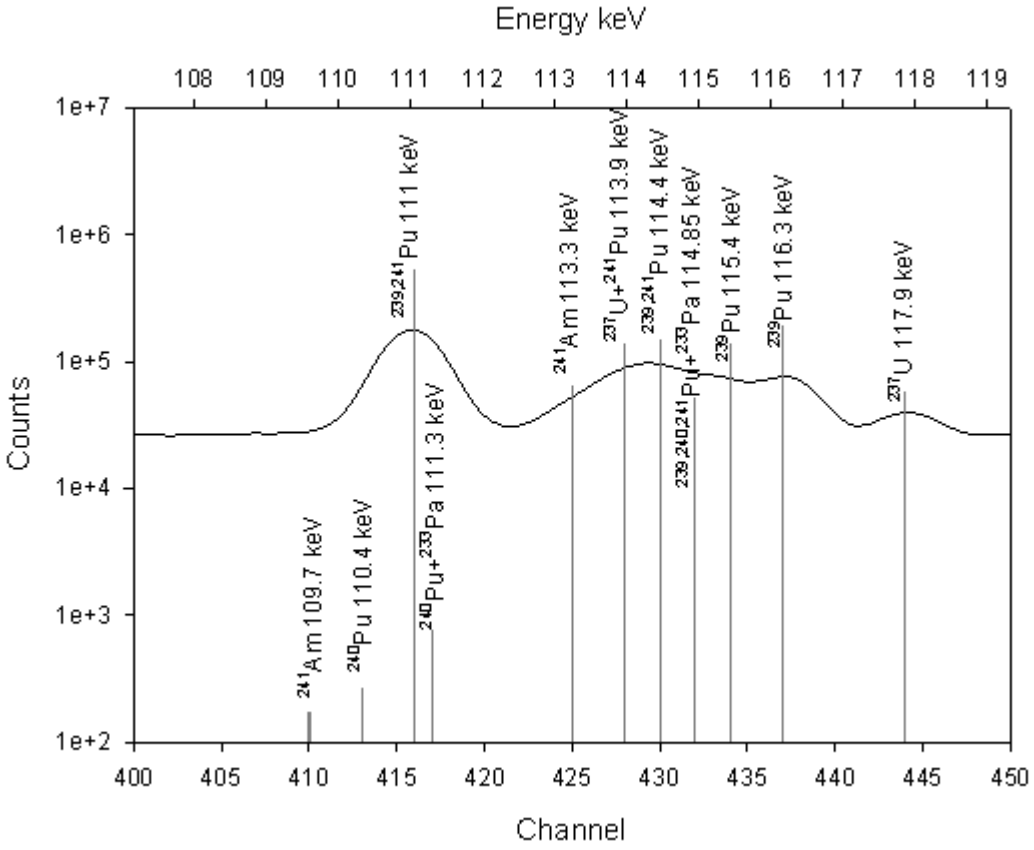
Pu-239	2618	645.9	65206.6
Pu-239	2632	649.3	3050.4
Pu-239	2643	652.1	28396.6
Am-241	2647	653	26421.9
Pu-239	2655	654.9	9046.7
Pu-239	2671	658.9	41873.1
Am-241	2686	662.4	251428.7
Pu-239	2694	664.5	7182.5
Am-241	2716	669.8	266.2
Pu-239	2733	674	1780.8
Am-241	2742	676	450.7
Am-241	2758	680.1	2180.8
Pu-239	2783	686.2	3882.8
Pu-240	2789	687.6	2789.4
Am-241	2794	688.8	21162.9
Pu-239	2802	690.7	3933.7
Am-241	2814	693.6	2615.4
Am-241	2826	696.6	3534.8
Pu-240	2833	698.1	25.7
Pu-239	2845	701	2245.2
Pu-239	2856	703.7	17331.5
Pu-238	2865	706	2.8
Pu-238	2875	708.3	21.7
Am-241	2879	709.5	4544.5
Pu-239	2900	714.6	347.7
Pu-239	2916	718.2	12333.6
Am-241	2931	722	139572.6
Pu-239	2955	727.8	5475.6
Am-241	2963	729.7	928.9
Am-241	2970	731.5	334.1
Am-241	2994	737.3	5715.7
Pu-238	3017	742.8	277.6
Am-241	3071	755.9	5451.2
Pu-239	3072	756.2	12428.8
Am-241	3085	759.5	1218
Am-241	3103	763.9	142.1
Pu-238	3114	766.4	1179.2
Am-241	3116	767	3589.6
Pu-239	3125	769.2	22672
Pu-239	3128	769.9	8005.4
Am-241	3131	770.5	3591.2
Am-241	3138	772.4	1910.2
Am-241	3158	777.2	43.1
Pu-239	3168	779.5	592.3
Am-241	3173	780.7	181.3
Pu-238	3196	786.3	174.6
Am-241	3208	789.2	280.9
Pu-239	3222	792.6	89.2
Am-241	3260	801.9	938.3
Pu-238	3270	804.4	6.5
Pu-238	3276	805.8	3.2
Pu-239	3286	808.2	656.2
Pu-238	3286	808.2	43.1
Am-241	3302	812	432.7
Pu-239	3309	813.9	276.8
Am-241	3332	819.3	290
Pu-239	3339	821.1	227.7
Am-241	3345	822.6	160.2
Am-241	3369	828.5	173.2
Pu-239	3371	828.8	616.6

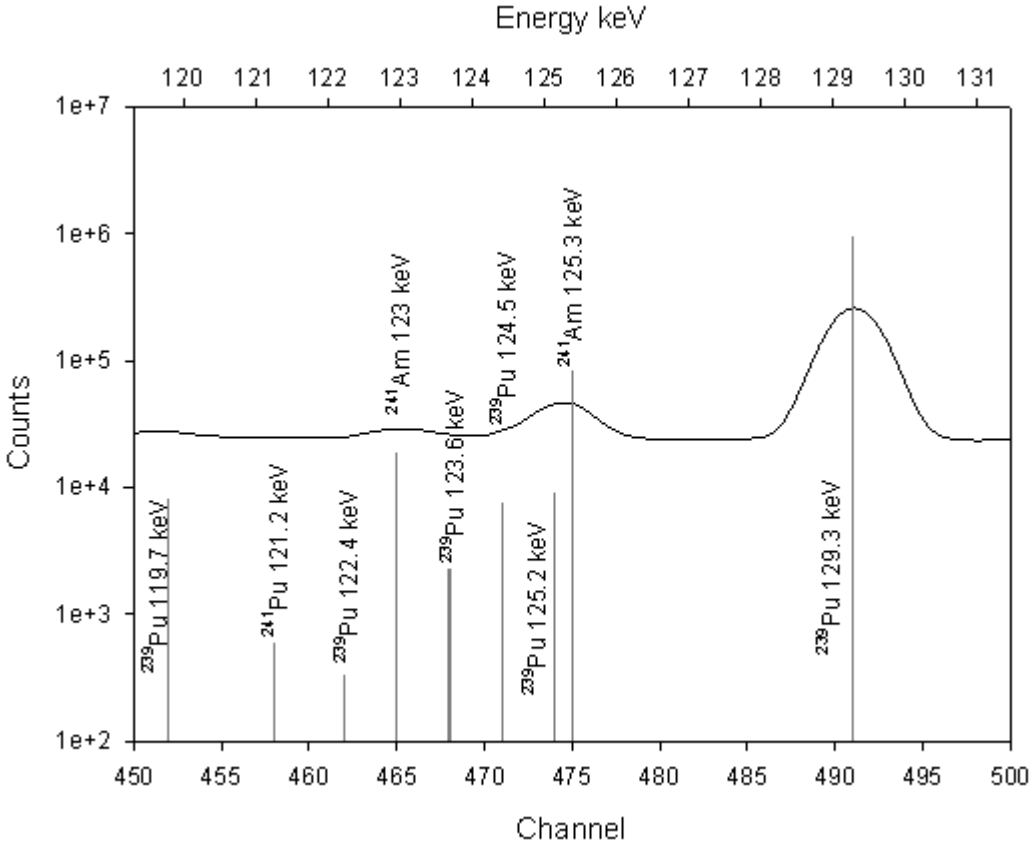
Pu-239	3384	831.9	111.7
Pu-239	3413	839	178.7
Pu-239	3432	843.8	598.8
Am-241	3465	851.6	272.8
Pu-238	3465	851.7	67.4
Am-241	3477	854.7	142.9
Am-241	3502	860.7	59.2
Am-241	3510	862.7	380.9
Am-241	3551	872.7	506.5
Pu-240	3557	874.1	607.5
Pu-239	3577	879	223.3
Pu-238	3584	880.5	8.6
Pu-238	3595	883.2	41.4
Am-241	3612	887.5	160.1
Pu-239	3627	891.1	343.7
Am-241	3657	898.4	51.9
Am-241	3674	902.5	216.2
Pu-238	3682	904.4	5.4
Am-241	3715	912.4	181.4
Am-241	3752	921.5	138.1
Pu-238	3774	926.7	31.1
Am-241	3782	928.8	38.8
Pu-239	3829	940.1	186.8
Pu-238	3836	941.9	25.2
Am-241	3852	945.7	40.2
Am-241	3893	955.7	417.3
Pu-239	3896	956.4	248.7
Pu-240	3940	967	52
Pu-239	3992	979.7	124
Pu-238	3995	980.4	4.3
Pu-239	4022	986.9	92.9
Pu-239	4045	992.6	119.4
Pu-238	4080	1001	51.9
Pu-239	4099	1005.6	60.8
Pu-238	4247	1041.7	11.4
Pu-239	4311	1057.3	193.6

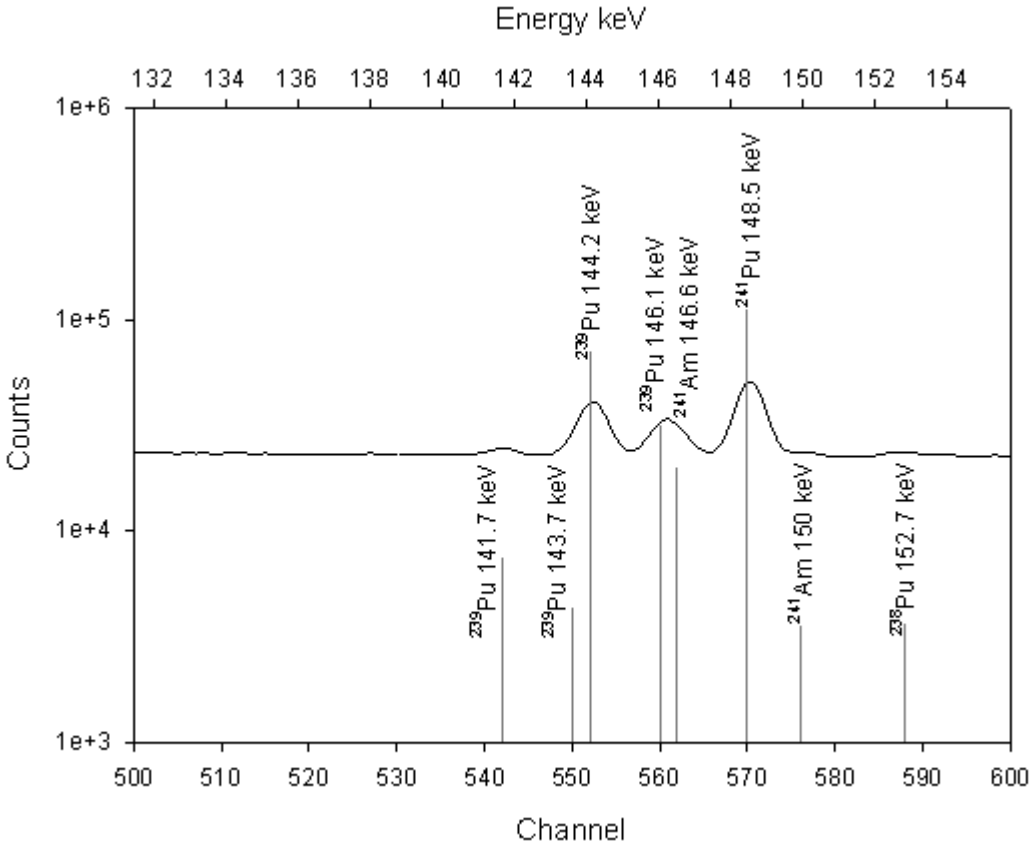
Table A2. Constituent photopeaks for the simulation of Scenario 2.

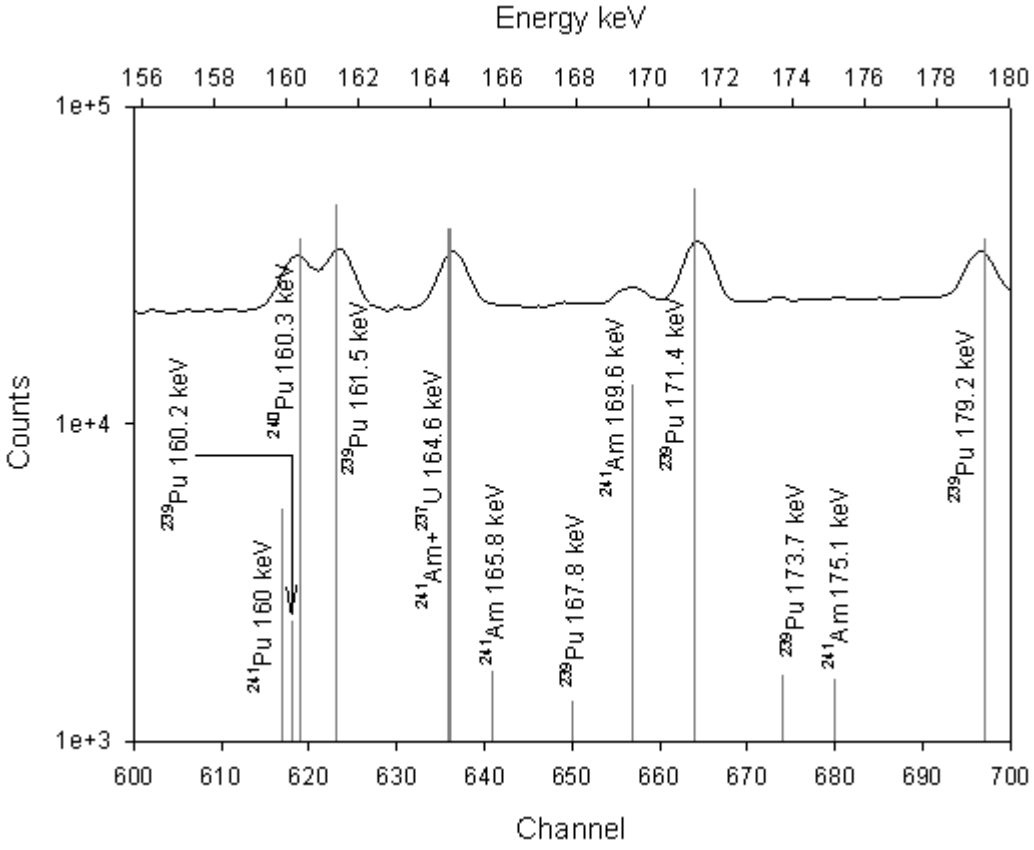

Energy keV
55
60
65
70
75
80
1e+6
1e+5
1e+4
1e+3
1e+2
Counts
241Am 59.5 keV
239Pu+241Am 67.6 keV
239Pu 68.7 keV
241Am 69.8 keV
239Pu 164.4 keV
241Pu 77.1keV
239Pu 77.6 keV
239Pu 78.4 keV
170
180
190
200
210
220
230
240
250
260
270
280
290
Channel

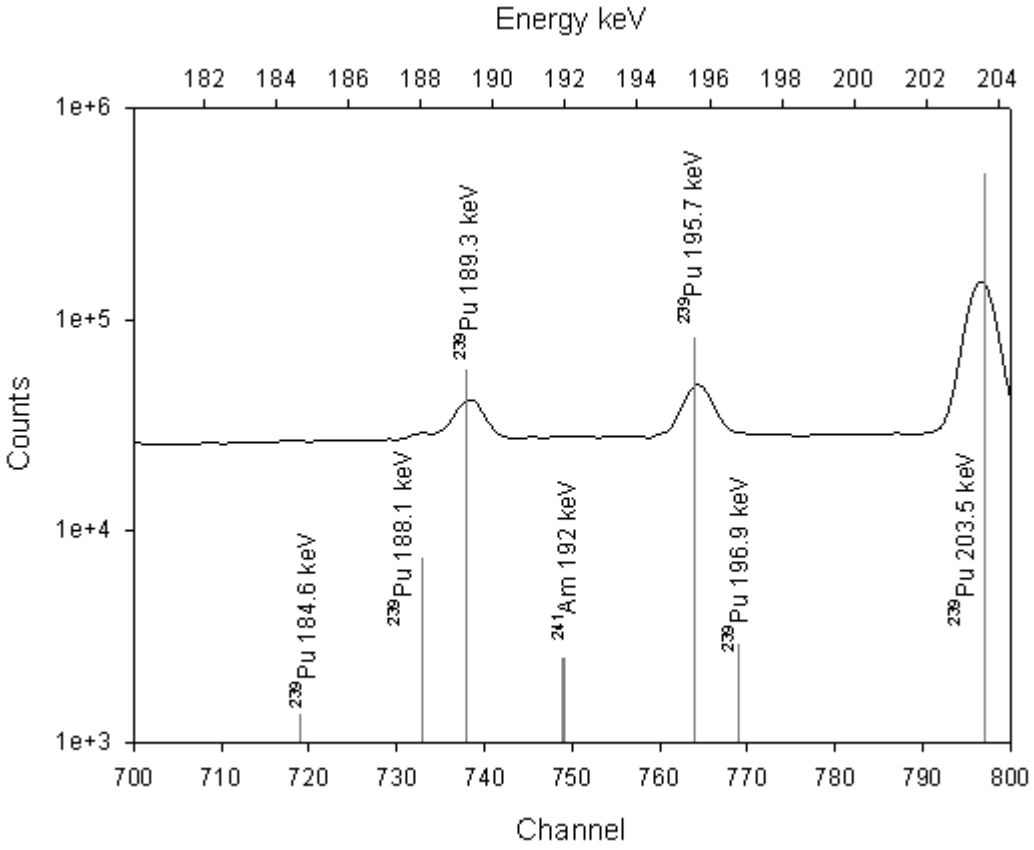

Energy keV
86
88
90
92
94
96
98
100
102
104
106
1e+6
1e+5
1e+4
1e+3
1e+2
Counts
239Pu 98.8 keV
241Am 99 keV
237Np 86.5 keV + 233Pa 86.8 keV
239Pu 89.6 keV
238,239,240,241Pu+237Np+233Pa 94.7 keV
241Am+237U 97.1keV
238,239,241,241Pu+233Pa 98.4 keV
238Pu 99.9 keV
237U+241Am 101.1 keV
241Am+239Pu 103 keV
241Pu 103.7 keV
240Pu 104.2 keV
310
315
320
325
330
335
340
345
350
355
360
365
370
375
380
385
390
395
400
Channel

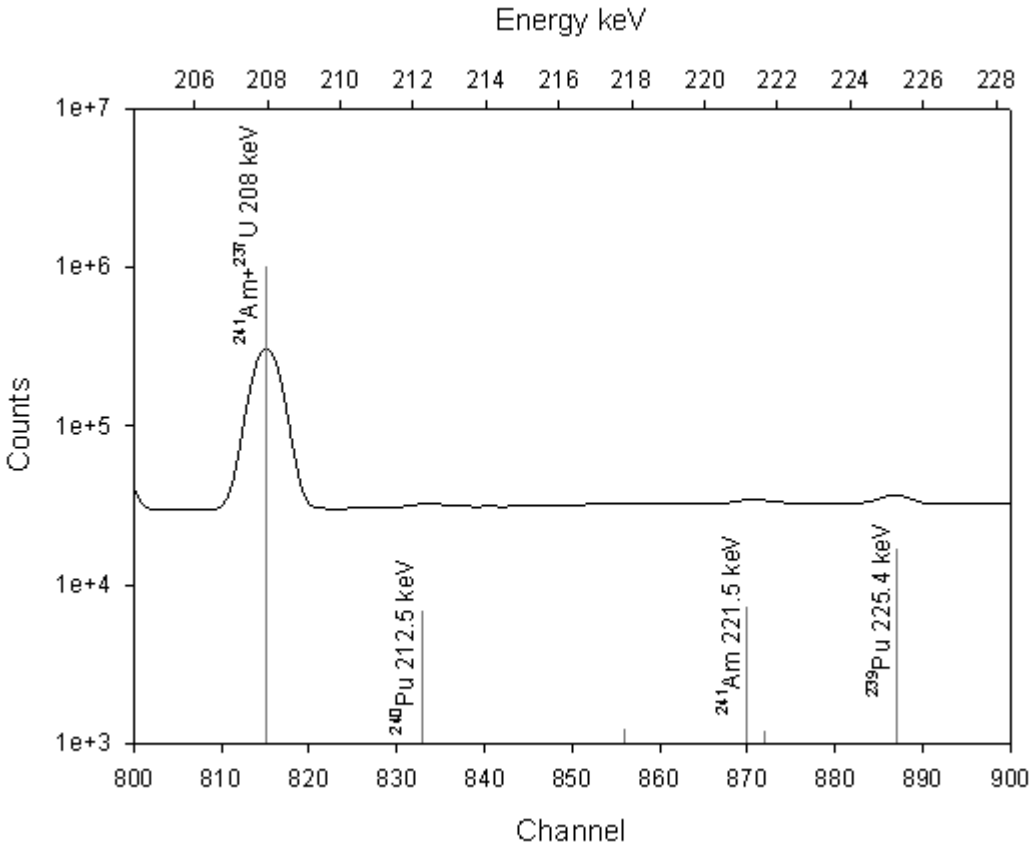

Energy keV
Counts
Channel
^{241}Am 109.7 keV
^{240}Pu 110.4 keV
^{240}Pu+^{233}Pa 111.3 keV
^{239,241}Pu 111 keV
^{241}Am 113.3 keV
^{237}U+^{241}Pu 113.9 keV
^{239,241}Pu 114.4 keV
^{239,240,241}Pu+^{233}Pa 114.85 keV
^{239}Pu 115.4 keV
^{239}Pu 116.3 keV
^{237}U 117.9 keV

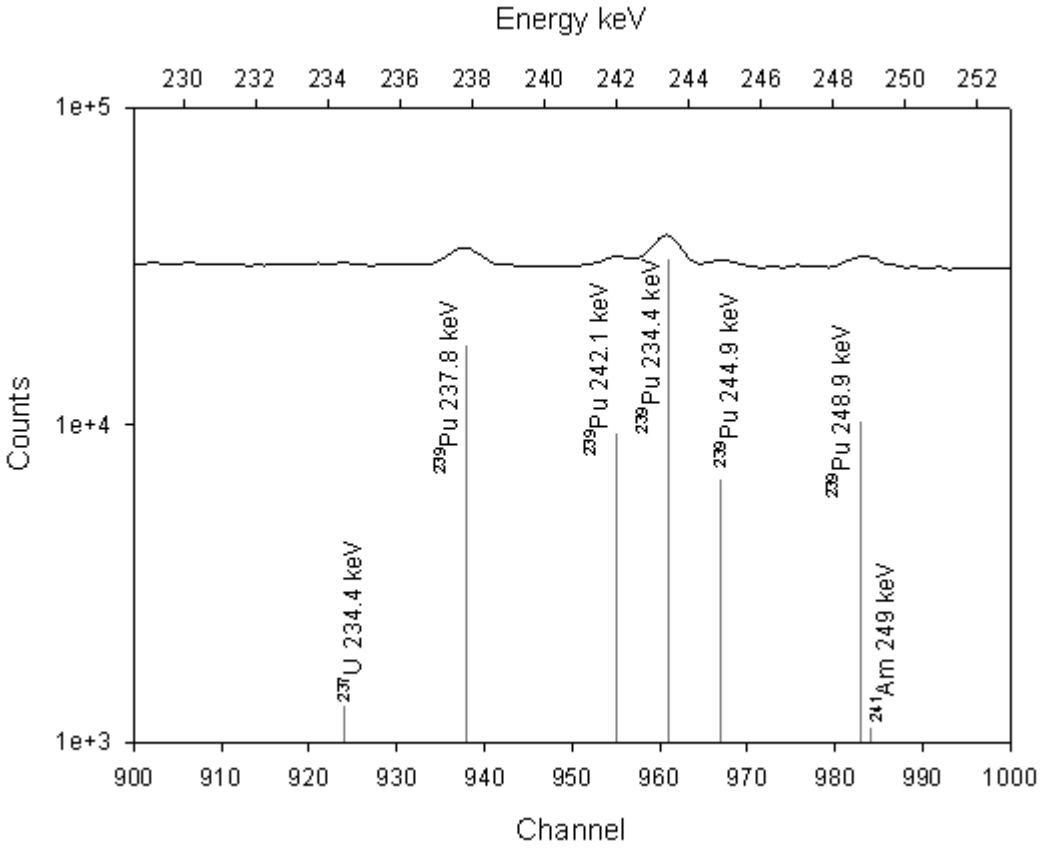

Energy keV
Counts
Channel
^{239}Pu 119.7 keV
^{241}Pu 121.2 keV
^{239}Pu 122.4 keV
^{241}Am 123 keV
^{239}Pu 123.6 keV
^{239}Pu 124.5 keV
^{241}Am 125.3 keV
^{239}Pu 125.2 keV
^{239}Pu 129.3 keV

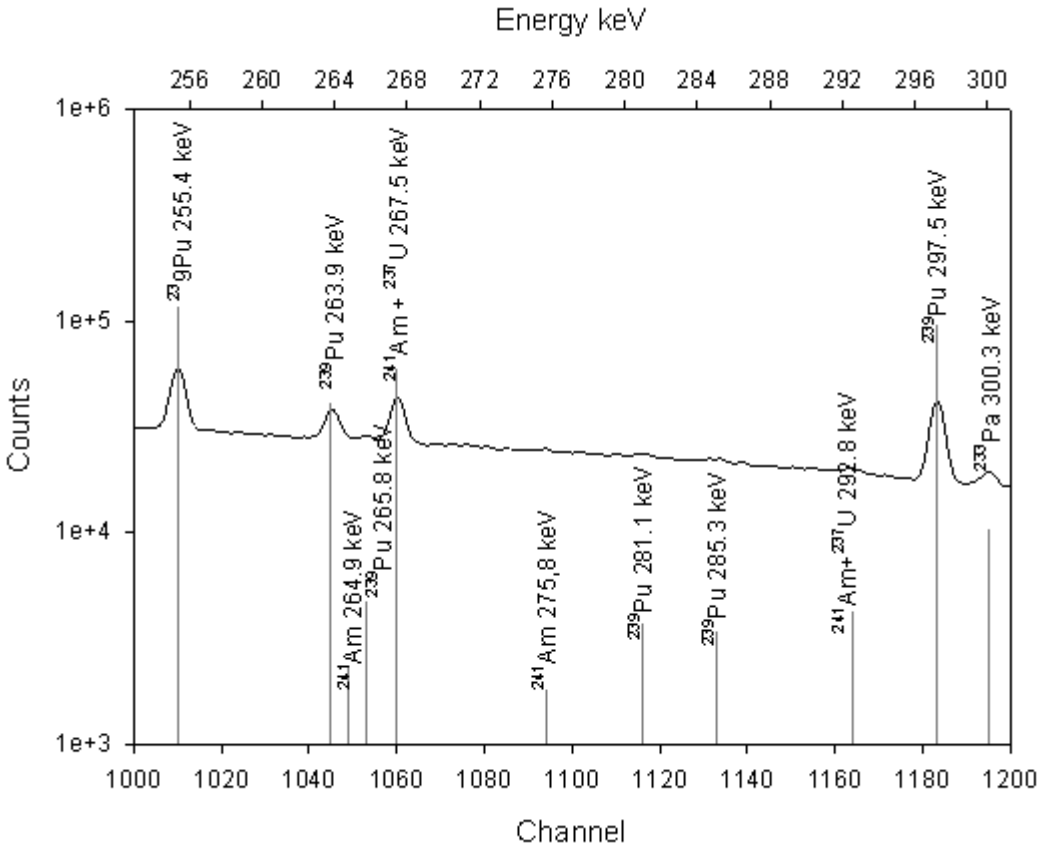

Energy keV
132 134 136 138 140 142 144 146 148 150 152 154
1e+6
1e+5
1e+4
1e+3
Counts
239Pu 141.7 keV
239Pu 143.7 keV
239Pu 144.2 keV
239Pu 146.1 keV
241Am 146.6 keV
241Pu 148.5 keV
241Am 150 keV
238Pu 152.7 keV
500 510 520 530 540 550 560 570 580 590 600
Channel

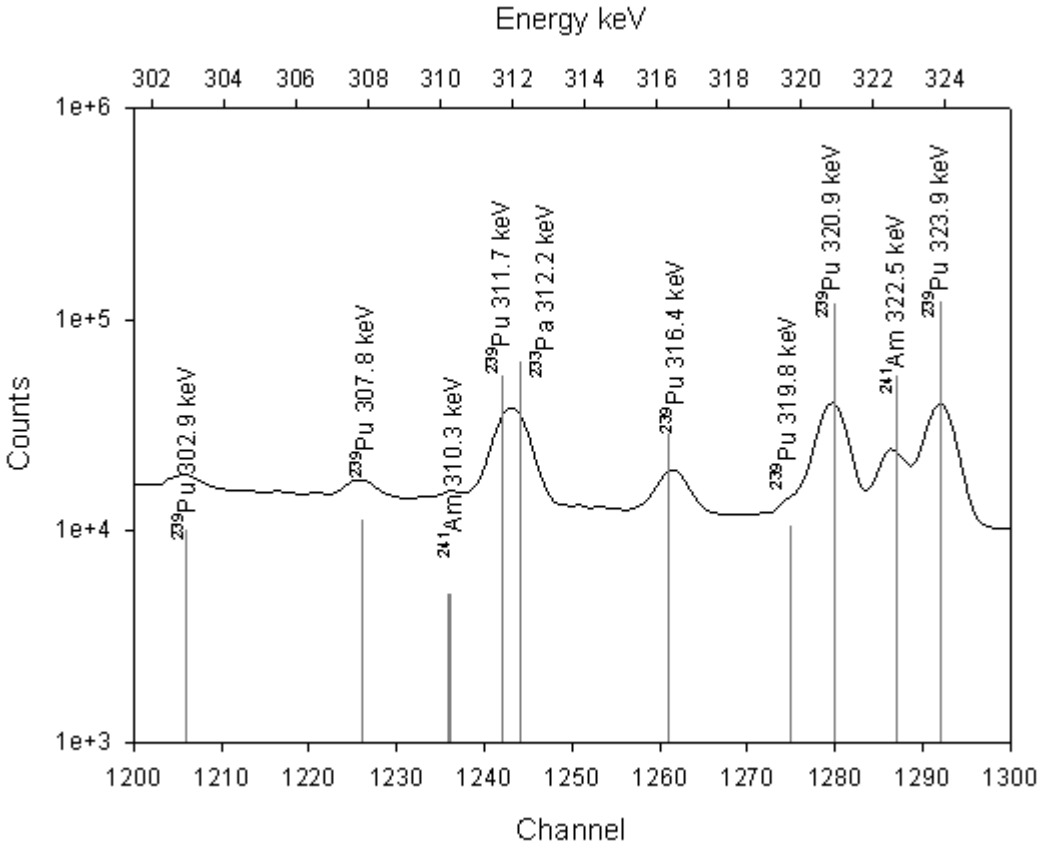

Energy keV
156 158 160 162 164 166 168 170 172 174 176 178 180
1e+5
1e+4
1e+3
Counts
239Pu 160.2 keV
241Pu 160 keV
240Pu 160.3 keV
239Pu 161.5 keV
241Am+237U 164.6 keV
241Am 165.8 keV
239Pu 167.8 keV
241Am 169.6 keV
239Pu 171.4 keV
239Pu 173.7 keV
241Am 175.1 keV
239Pu 179.2 keV
600 610 620 630 640 650 660 670 680 690 700
Channel

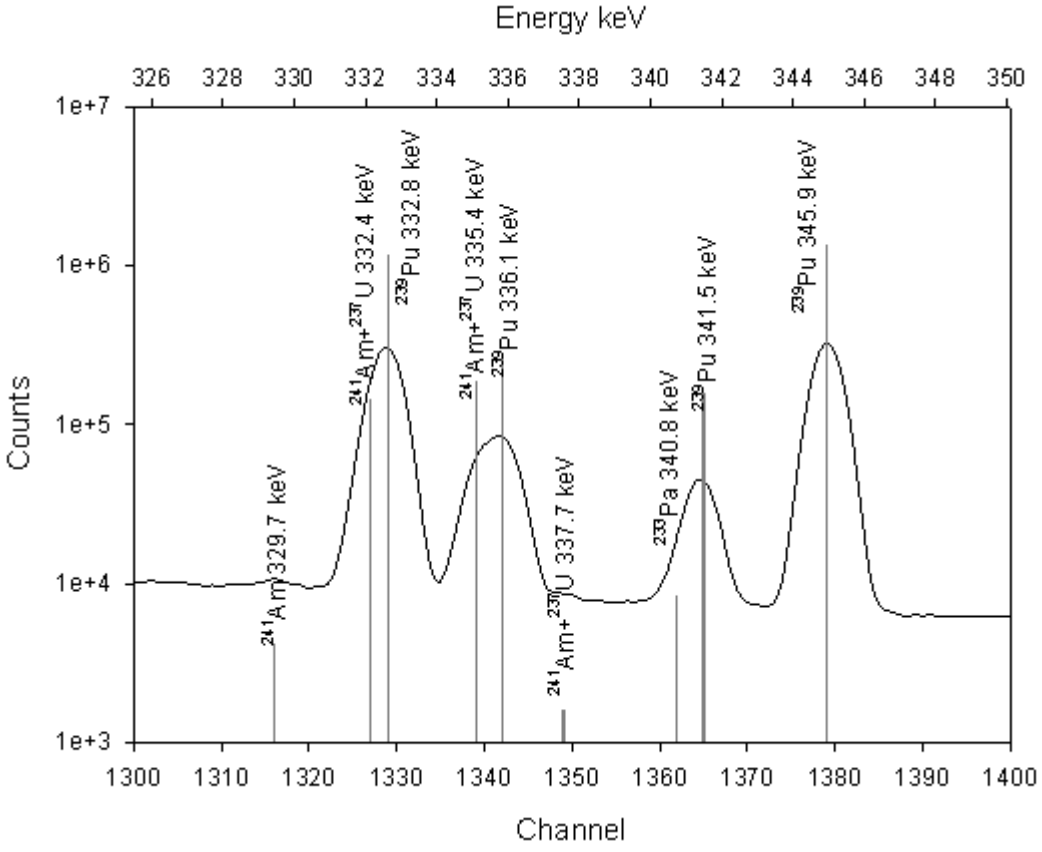

Energy keV
182 184 186 188 190 192 194 196 198 200 202 204
1e+6
1e+5
1e+4
1e+3
Counts
239Pu 189.3 keV
239Pu 195.7 keV
239Pu 188.1 keV
241Am 192 keV
239Pu 196.9 keV
239Pu 203.5 keV
239Pu 184.6 keV
700 710 720 730 740 750 760 770 780 790 800
Channel

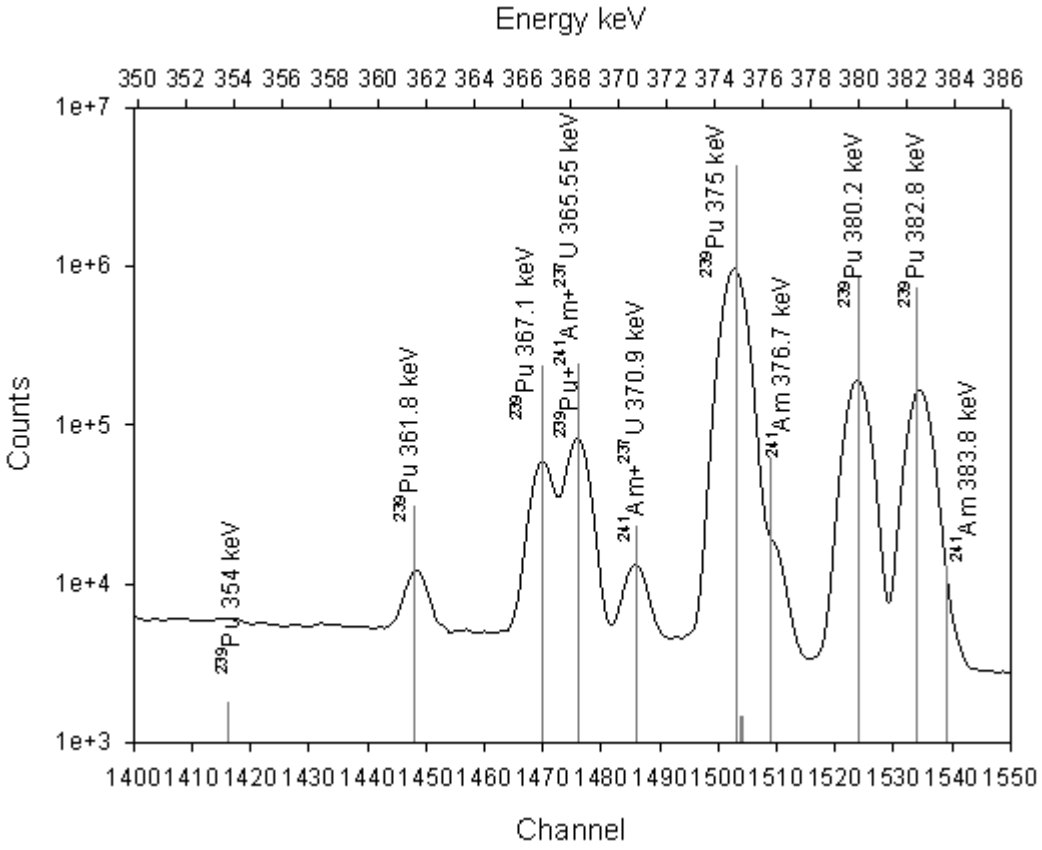

Energy keV
206 208 210 212 214 216 218 220 222 224 226 228
1e+7
1e+6
1e+5
1e+4
1e+3
Counts
241Am+237U 208 keV
240Pu 212.5 keV
241Am 221.5 keV
239Pu 225.4 keV
800 810 820 830 840 850 860 870 880 890 900
Channel

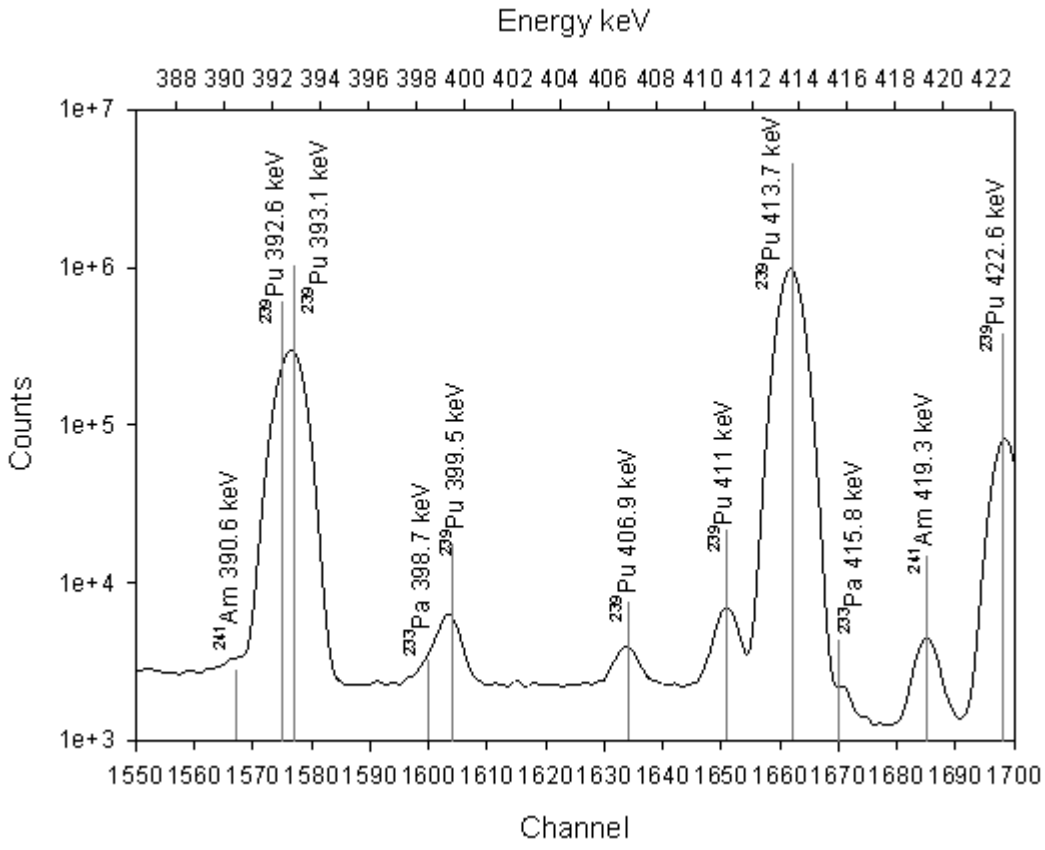

Energy keV
230 232 234 236 238 240 242 244 246 248 250 252
1e+5
1e+4
1e+3
Counts
900 910 920 930 940 950 960 970 980 990 1000
Channel
^{237}U 234.4 keV
^{239}Pu 237.8 keV
^{239}Pu 242.1 keV
^{239}Pu 234.4 keV
^{239}Pu 244.9 keV
^{239}Pu 248.9 keV
^{241}Am 249 keV

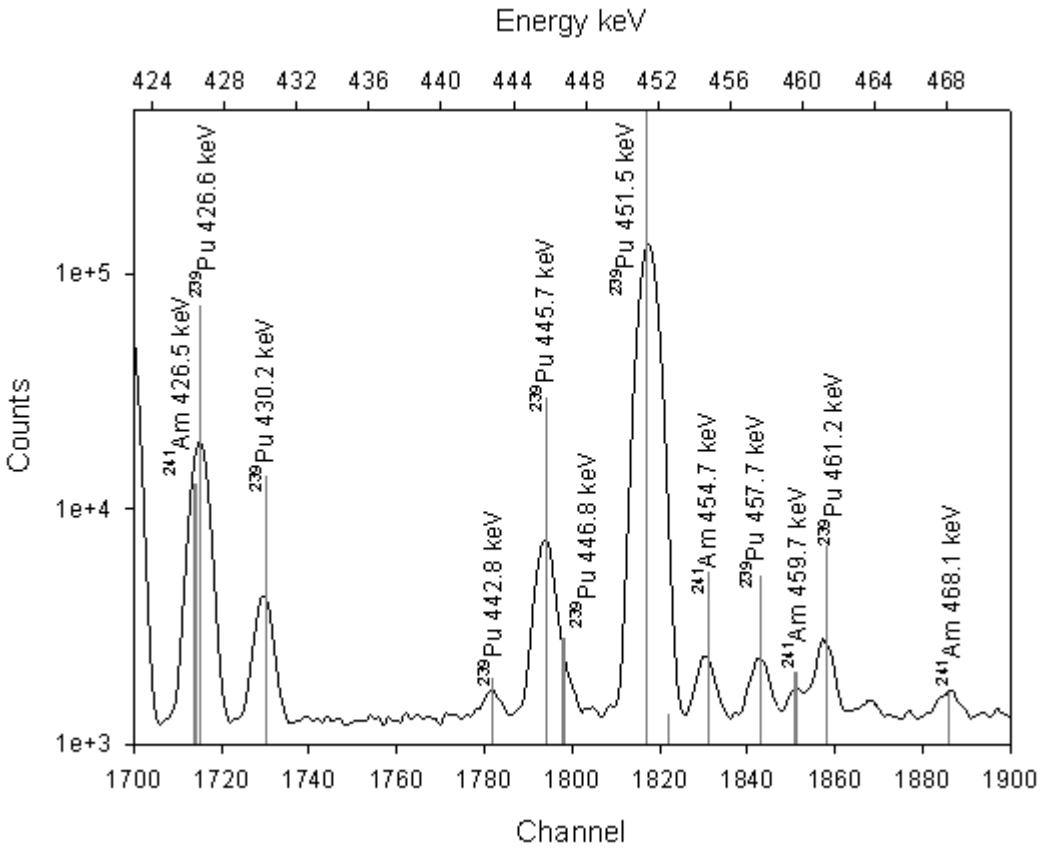

Energy keV
256 260 264 268 272 276 280 284 288 292 296 300
1e+6
1e+5
1e+4
1e+3
Counts
1000 1020 1040 1060 1080 1100 1120 1140 1160 1180 1200
Channel
^{239}Pu 255.4 keV
^{239}Pu 263.9 keV
^{241}Am + ^{237}U 267.5 keV
^{241}Am 264.9 keV
^{239}Pu 265.8 keV
^{241}Am 275,8 keV
^{239}Pu 281.1 keV
^{239}Pu 285.3 keV
^{241}Am+^{237}U 292.8 keV
^{239}Pu 297.5 keV
^{233}Pa 300.3 keV

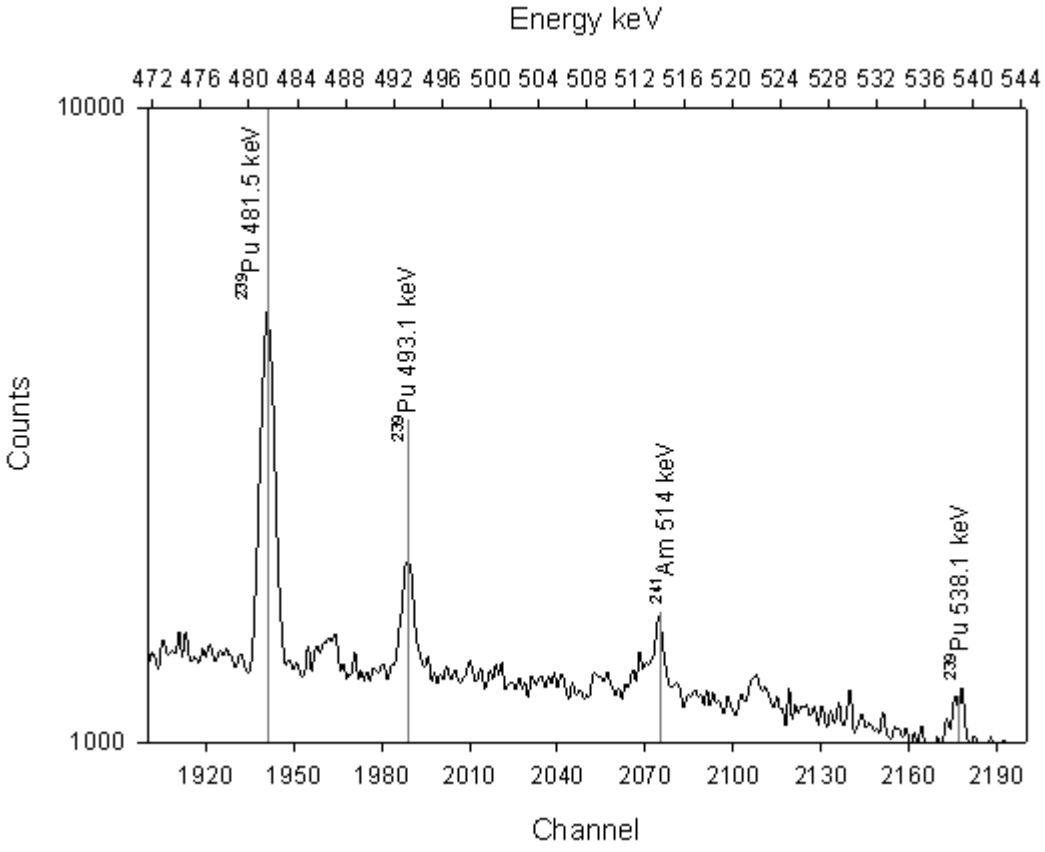

Energy keV
302 304 306 308 310 312 314 316 318 320 322 324
1e+6
1e+5
1e+4
1e+3
Counts
239Pu 302.9 keV
239Pu 307.8 keV
241Am 310.3 keV
239Pu 311.7 keV
233Pa 312.2 keV
239Pu 316.4 keV
239Pu 319.8 keV
239Pu 320.9 keV
241Am 322.5 keV
239Pu 323.9 keV
1200 1210 1220 1230 1240 1250 1260 1270 1280 1290 1300
Channel

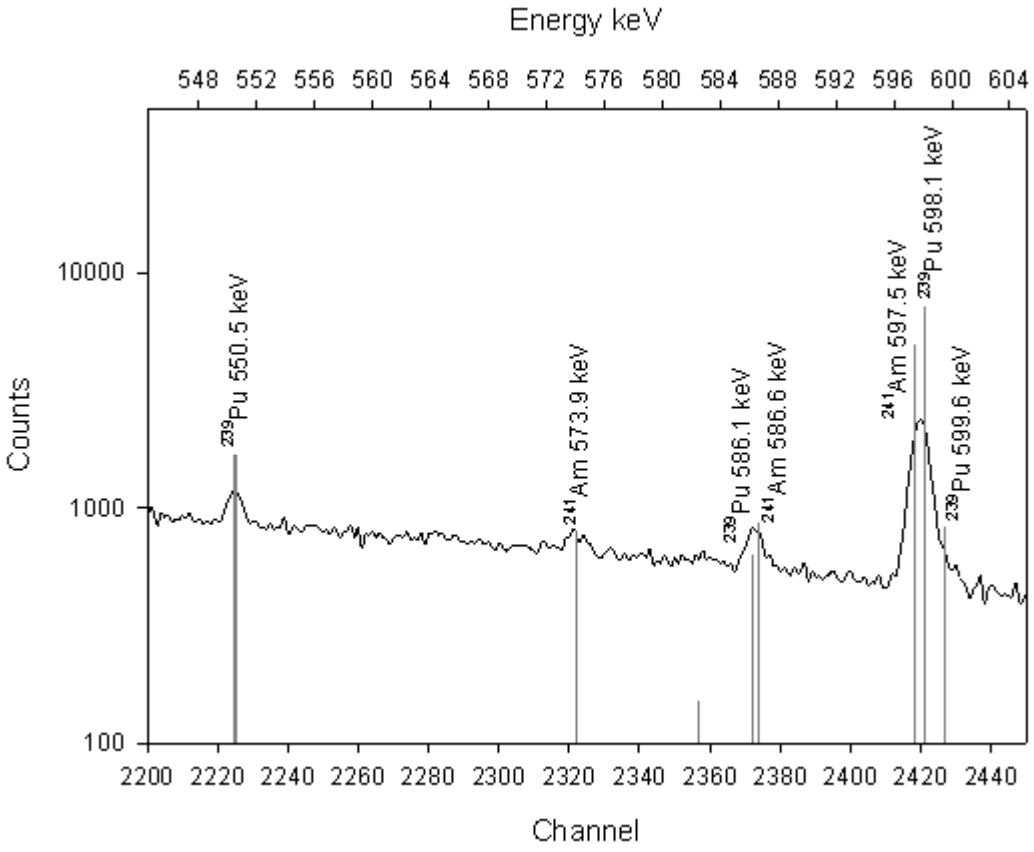

Energy keV
326 328 330 332 334 336 338 340 342 344 346 348 350
1e+7
1e+6
1e+5
1e+4
1e+3
Counts
241Am 329.7 keV
241Am+237U 332.4 keV
239Pu 332.8 keV
241Am+237U 335.4 keV
239Pu 336.1 keV
241Am+237U 337.7 keV
233Pa 340.8 keV
239Pu 341.5 keV
239Pu 345.9 keV
1300 1310 1320 1330 1340 1350 1360 1370 1380 1390 1400
Channel

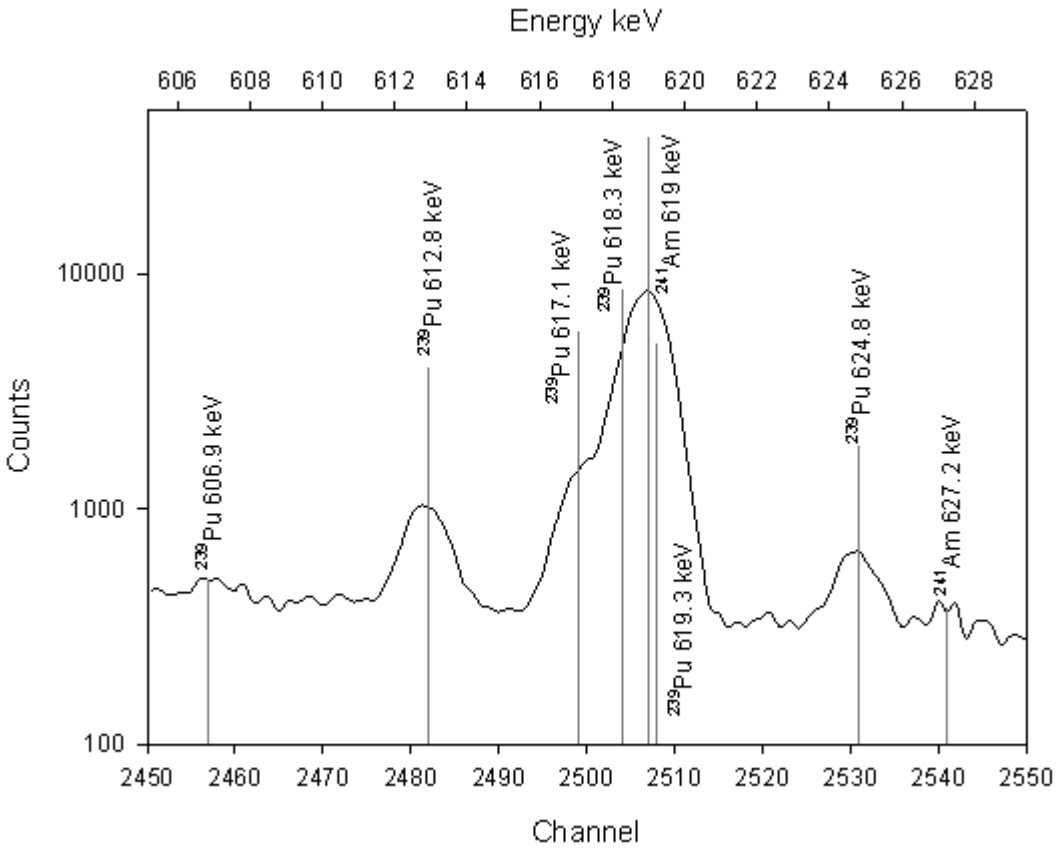

Energy keV
350 352 354 356 358 360 362 364 366 368 370 372 374 376 378 380 382 384 386
1e+7
1e+6
1e+5
1e+4
1e+3
Counts
239Pu 354 keV
239Pu 361.8 keV
239Pu 367.1 keV
239Pu+241Am+237U 365.55 keV
241Am+237U 370.9 keV
239Pu 375 keV
241Am 376.7 keV
239Pu 380.2 keV
239Pu 382.8 keV
241Am 383.8 keV
1400 1410 1420 1430 1440 1450 1460 1470 1480 1490 1500 1510 1520 1530 1540 1550
Channel

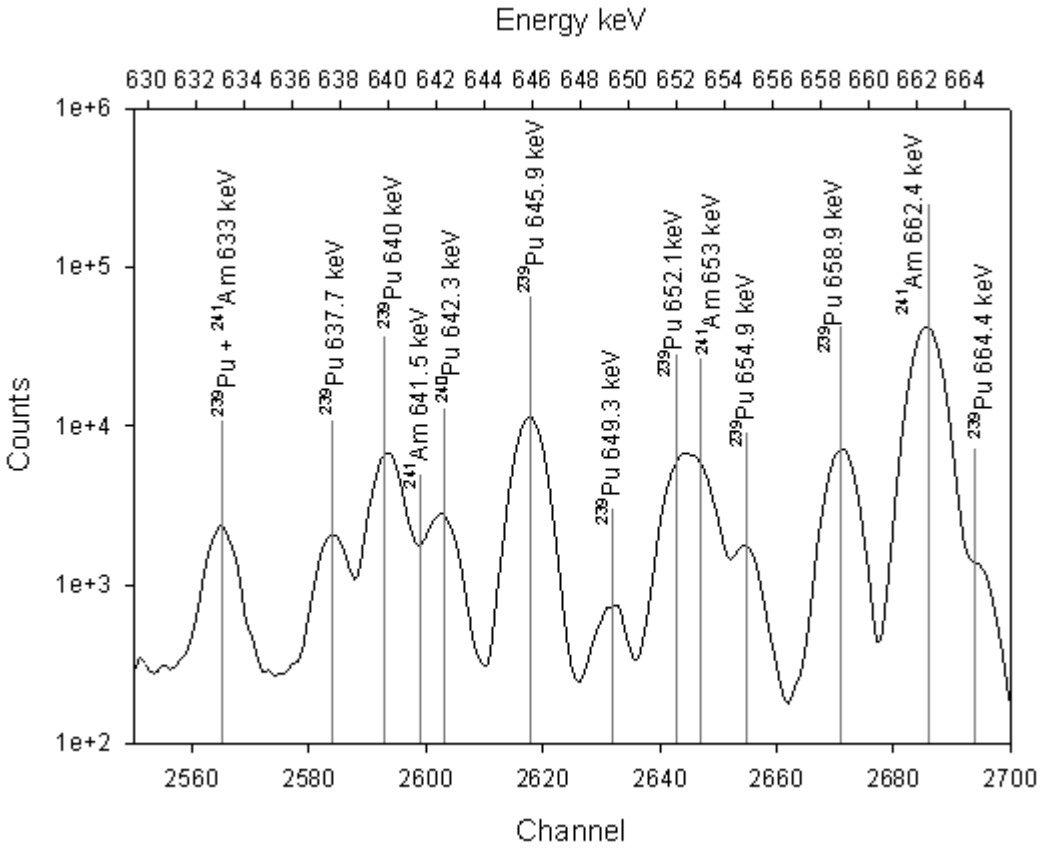

Energy keV
388 390 392 394 396 398 400 402 404 406 408 410 412 414 416 418 420 422
1e+7
1e+6
1e+5
1e+4
1e+3
Counts
241Am 390.6 keV
239Pu 392.6 keV
239Pu 393.1 keV
233Pa 398.7 keV
239Pu 399.5 keV
239Pu 406.9 keV
239Pu 411 keV
239Pu 413.7 keV
233Pa 415.8 keV
241Am 419.3 keV
239Pu 422.6 keV
1550 1560 1570 1580 1590 1600 1610 1620 1630 1640 1650 1660 1670 1680 1690 1700
Channel

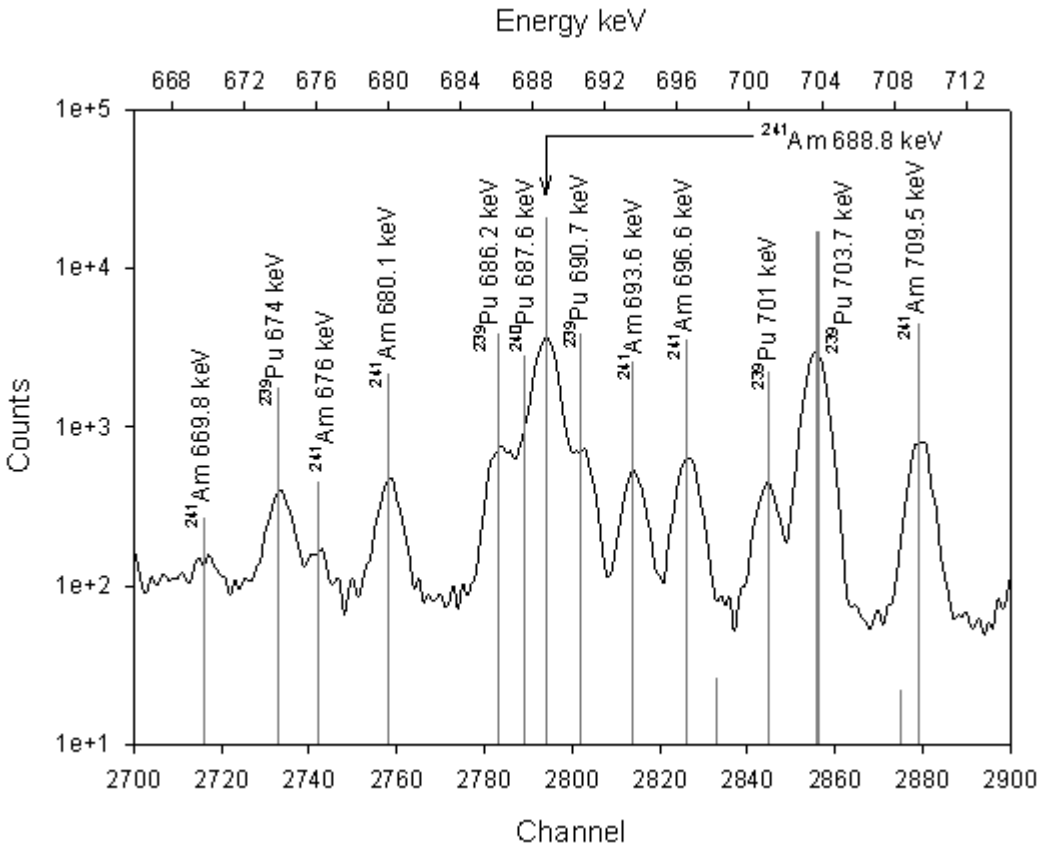

Energy keV
424 428 432 436 440 444 448 452 456 460 464 468
Counts
1e+5
1e+4
1e+3
241Am 426.5 keV
239Pu 426.6 keV
239Pu 430.2 keV
239Pu 442.8 keV
239Pu 445.7 keV
239Pu 446.8 keV
239Pu 451.5 keV
241Am 454.7 keV
239Pu 457.7 keV
241Am 459.7 keV
239Pu 461.2 keV
241Am 468.1 keV
1700 1720 1740 1760 1780 1800 1820 1840 1860 1880 1900
Channel

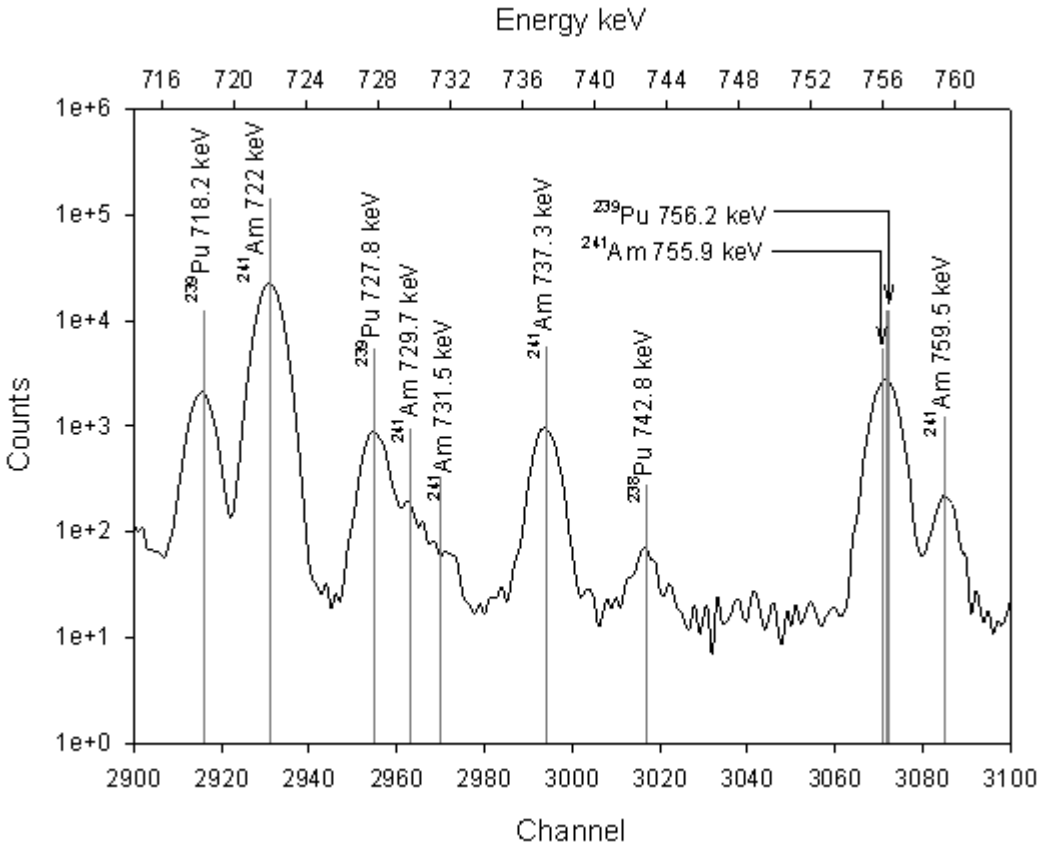

Energy keV
472 476 480 484 488 492 496 500 504 508 512 516 520 524 528 532 536 540 544
Counts
10000
1000
239Pu 481.5 keV
239Pu 493.1 keV
241Am 514 keV
239Pu 538.1 keV
1920 1950 1980 2010 2040 2070 2100 2130 2160 2190
Channel

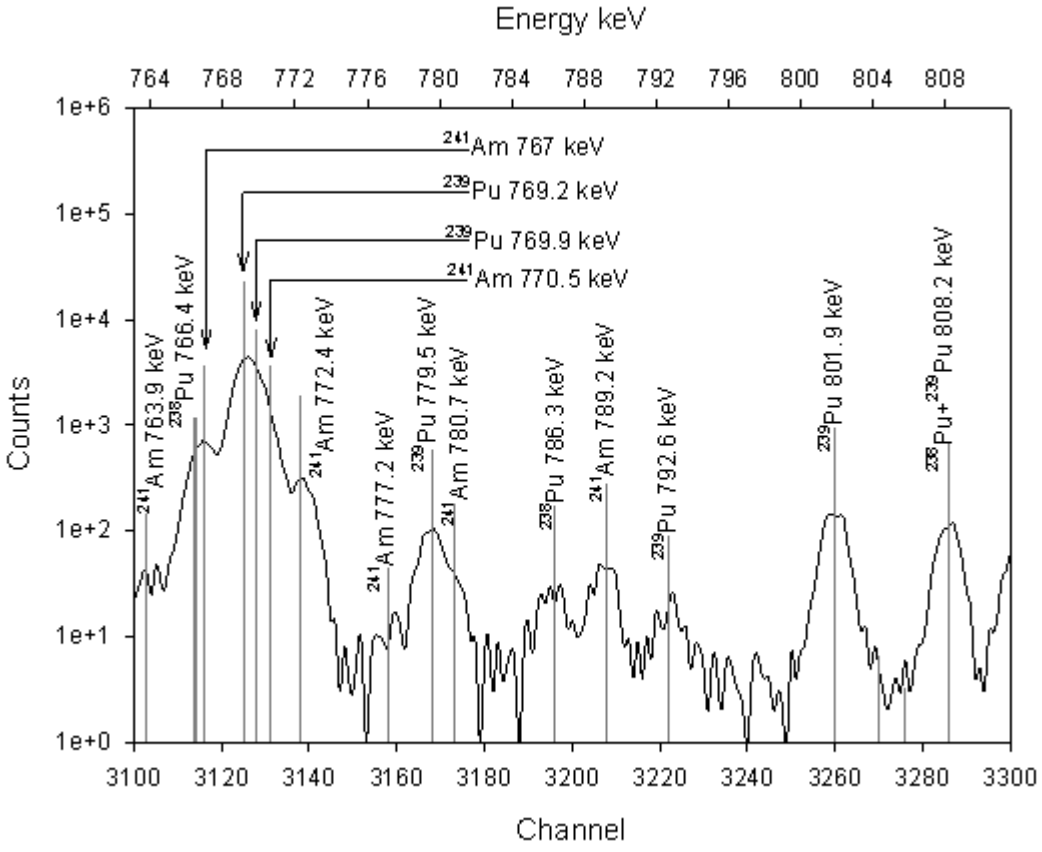

Energy keV
548 552 556 560 564 568 572 576 580 584 588 592 596 600 604
10000
1000
100
Counts
239Pu 550.5 keV
241Am 573.9 keV
239Pu 586.1 keV
241Am 586.6 keV
241Am 597.5 keV
239Pu 598.1 keV
239Pu 599.6 keV
2200 2220 2240 2260 2280 2300 2320 2340 2360 2380 2400 2420 2440
Channel


Energy keV
606 608 610 612 614 616 618 620 622 624 626 628
10000
1000
100
Counts
239Pu 606.9 keV
239Pu 612.8 keV
239Pu 617.1 keV
239Pu 618.3 keV
241Am 619 keV
239Pu 619.3 keV
239Pu 624.8 keV
241Am 627.2 keV
2450 2460 2470 2480 2490 2500 2510 2520 2530 2540 2550
Channel


Energy keV
630 632 634 636 638 640 642 644 646 648 650 652 654 656 658 660 662 664
1e+6
1e+5
1e+4
1e+3
1e+2
Counts
239Pu + 241Am 633 keV
239Pu 637.7 keV
239Pu 640 keV
241Am 641.5 keV
240Pu 642.3 keV
239Pu 645.9 keV
239Pu 649.3 keV
239Pu 652.1keV
241Am 653 keV
239Pu 654.9 keV
239Pu 658.9 keV
241Am 662.4 keV
239Pu 664.4 keV
2560 2580 2600 2620 2640 2660 2680 2700
Channel


Energy keV
668 672 676 680 684 688 692 696 700 704 708 712
1e+5
1e+4
1e+3
1e+2
1e+1
Counts
241Am 669.8 keV
239Pu 674 keV
241Am 676 keV
241Am 680.1 keV
239Pu 686.2 keV
240Pu 687.6 keV
241Am 688.8 keV
239Pu 690.7 keV
241Am 693.6 keV
241Am 696.6 keV
239Pu 701 keV
239Pu 703.7 keV
241Am 709.5 keV
2700 2720 2740 2760 2780 2800 2820 2840 2860 2880 2900
Channel


Energy keV
716 720 724 728 732 736 740 744 748 752 756 760
1e+6
1e+5
1e+4
1e+3
1e+2
1e+1
1e+0
Counts
239Pu 718.2 keV
241Am 722 keV
239Pu 727.8 keV
241Am 729.7 keV
241Am 731.5 keV
241Am 737.3 keV
238Pu 742.8 keV
239Pu 756.2 keV
241Am 755.9 keV
241Am 759.5 keV
2900 2920 2940 2960 2980 3000 3020 3040 3060 3080 3100
Channel


Energy keV
764 768 772 776 780 784 788 792 796 800 804 808
1e+6
1e+5
1e+4
1e+3
1e+2
1e+1
1e+0
Counts
241Am 767 keV
239Pu 769.2 keV
239Pu 769.9 keV
241Am 770.5 keV
241Am 763.9 keV
238Pu 766.4 keV
241Am 772.4 keV
241Am 777.2 keV
239Pu 779.5 keV
241Am 780.7 keV
238Pu 786.3 keV
241Am 789.2 keV
239Pu 792.6 keV
239Pu 801.9 keV
238Pu+239Pu 808.2 keV
3100 3120 3140 3160 3180 3200 3220 3240 3260 3280 3300
Channel

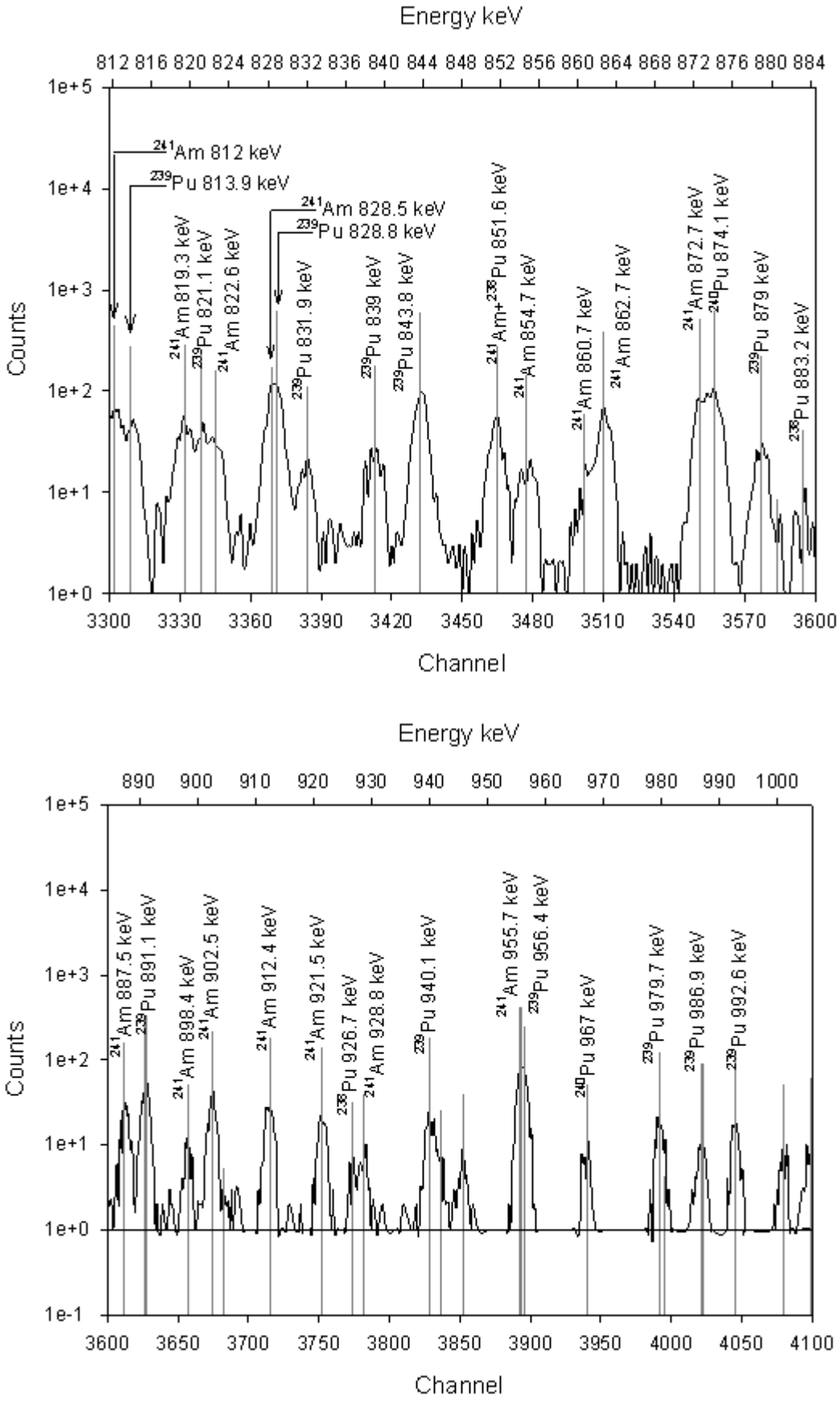
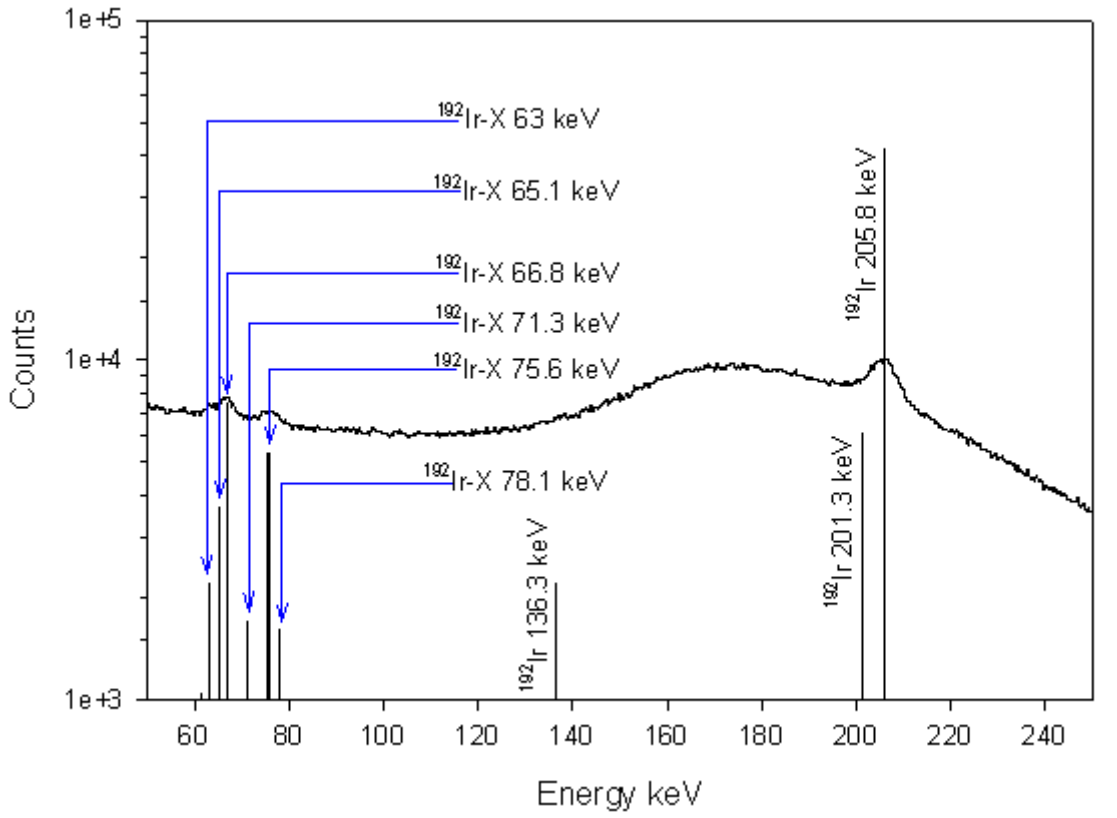


Figure A2. Assignation of constituent peaks for the spectrum of Scenario 2.

APPENDIX 3. Spectral information for Scenario 3.

Nuclide	HPGe Channel	Energy keV	HPGe Counts	HPGe FWHM keV	CdZnTe Channel	CdZnTe Counts	CdZnTe FWHM keV
^{192}Ir x-ray	283	61.5	5877.9	0.9	142	1046.8	3.44
^{192}Ir x-ray	291	63	12973.6	0.9	146	2214.7	3.48
^{192}Ir x-ray	303	65.1	22716.9	0.9	152	3678.1	3.54
^{192}Ir x-ray	312	66.8	48169.4	0.9	156	7508.7	3.59
^{192}Ir x-ray	337	71.3	11850.4	0.9	169	1699.6	3.71
^{192}Ir x-ray	350	73.6	3697.4	0.9	175	511.6	3.77
^{192}Ir x-ray	361	75.6	39679.3	0.9	180	5343.3	3.82
^{192}Ir x-ray	375	78.1	12335.2	0.9	187	1611.5	3.88
^{192}Ir	550	110.1	1187.1	0.9	275	119.4	4.6
^{192}Ir	695	136.3	23818.1	0.9	347	2203.3	5.12
^{192}Ir	918	177	660.6	0.9	459	56.1	5.84
^{192}Ir	1052	201.3	73578.4	0.9	526	6063.6	6.22
^{192}Ir	1076	205.8	511920.3	0.9	538	41851.5	6.29
^{192}Ir	1125	214.7	234	0.9	563	18.9	6.43
^{192}Ir	1485	280	312.5	0.9	742	23.7	7.34
^{192}Ir	1502	283.3	35362.8	0.9	751	2677.1	7.38
^{192}Ir	1572	296	3770675	0.9	786	283566.9	7.55
^{192}Ir	1641	308.5	3847282	0.91	820	282440.7	7.7
^{192}Ir	1676	314.8	5435.4	0.92	838	392.7	7.78
^{192}Ir	1676	314.8	262.1	0.92	838	18.9	7.78
^{192}Ir	1685	316.5	10449310	0.93	843	751651.6	7.8
^{192}Ir	1756	329.3	2275.2	0.95	878	158.7	7.96
^{192}Ir	2004	374.5	81392	1.01	1002	5140.3	8.49
^{192}Ir	2229	415.4	551.3	1.06	1114	32.2	8.94
^{192}Ir	2235	416.5	69903.3	1.06	1117	4071.5	8.95
^{192}Ir	2257	420.5	7677.9	1.07	1129	443.9	8.99
^{192}Ir	2518	468.1	4620743	1.13	1259	246248.7	9.49
^{192}Ir	2565	476.5	318.5	1.14	1282	16.7	9.57
^{192}Ir	2609	484.6	300142.3	1.15	1305	15577.6	9.65
^{192}Ir	2613	485.3	207.2	1.15	1307	10.7	9.66
^{192}Ir	2634	489	41490.3	1.15	1317	2138.3	9.7
^{192}Ir	3181	588.6	371036.3	1.26	1591	16579.2	10.64
^{192}Ir	3207	593.4	3481	1.27	1604	154.6	10.68
^{192}Ir	3268	604.4	664182.8	1.28	1634	29071.2	10.78
^{192}Ir	3312	612.5	424219.3	1.29	1656	18377.3	10.85
^{192}Ir	3815	704	384.2	1.38	1908	14.9	11.63
^{192}Ir	4155	765.8	101.9	1.44	2078	3.7	12.13
^{192}Ir	4808	884.5	18078.7	1.55	2404	585	13.04
^{192}Ir	5781	1061.5	2868.8	1.7	2891	80.2	14.28

Table A3. Comparison of CdZnTe and HPGe spectra for the source of Scenario 3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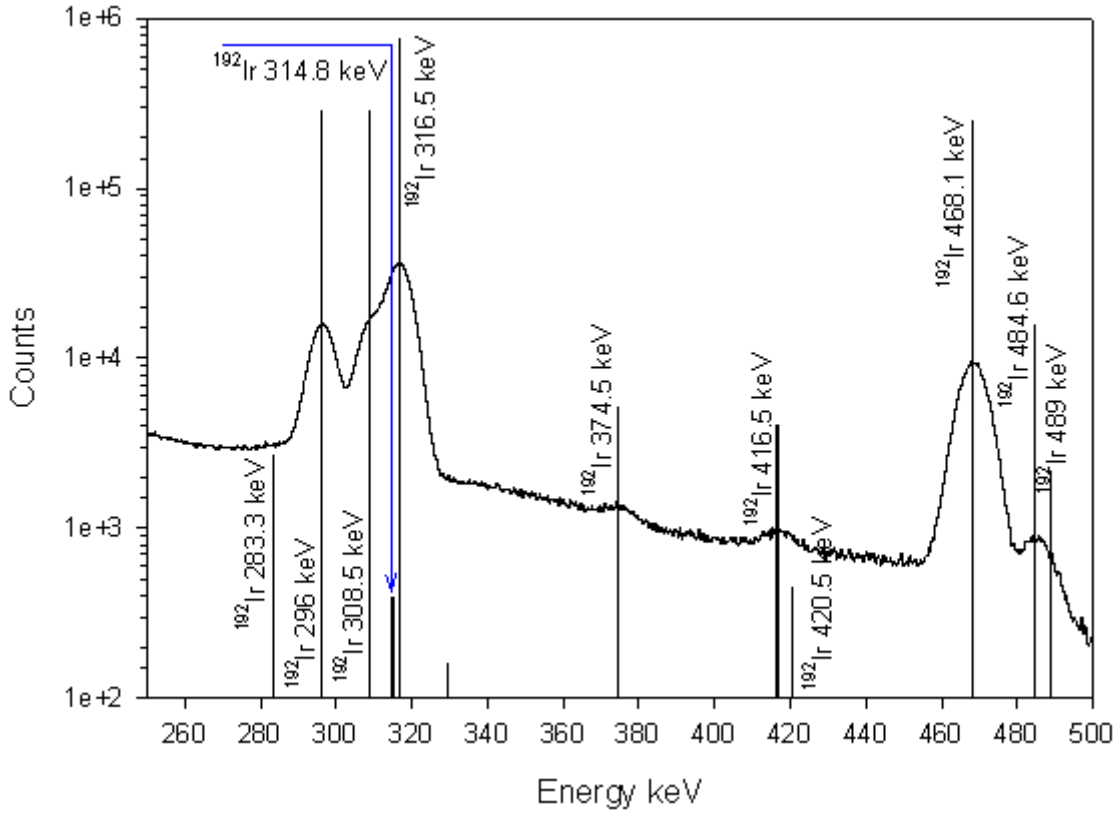
60
80
100
120
140
160
180
200
220
240
Energy keV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1e+5
1e+4
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1e+2
Counts
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192Ir 308.5 keV
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192Ir 420.5 keV
192Ir 468.1 keV
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260
280
300
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340
360
380
400
420
440
460
480
500
Energy keV

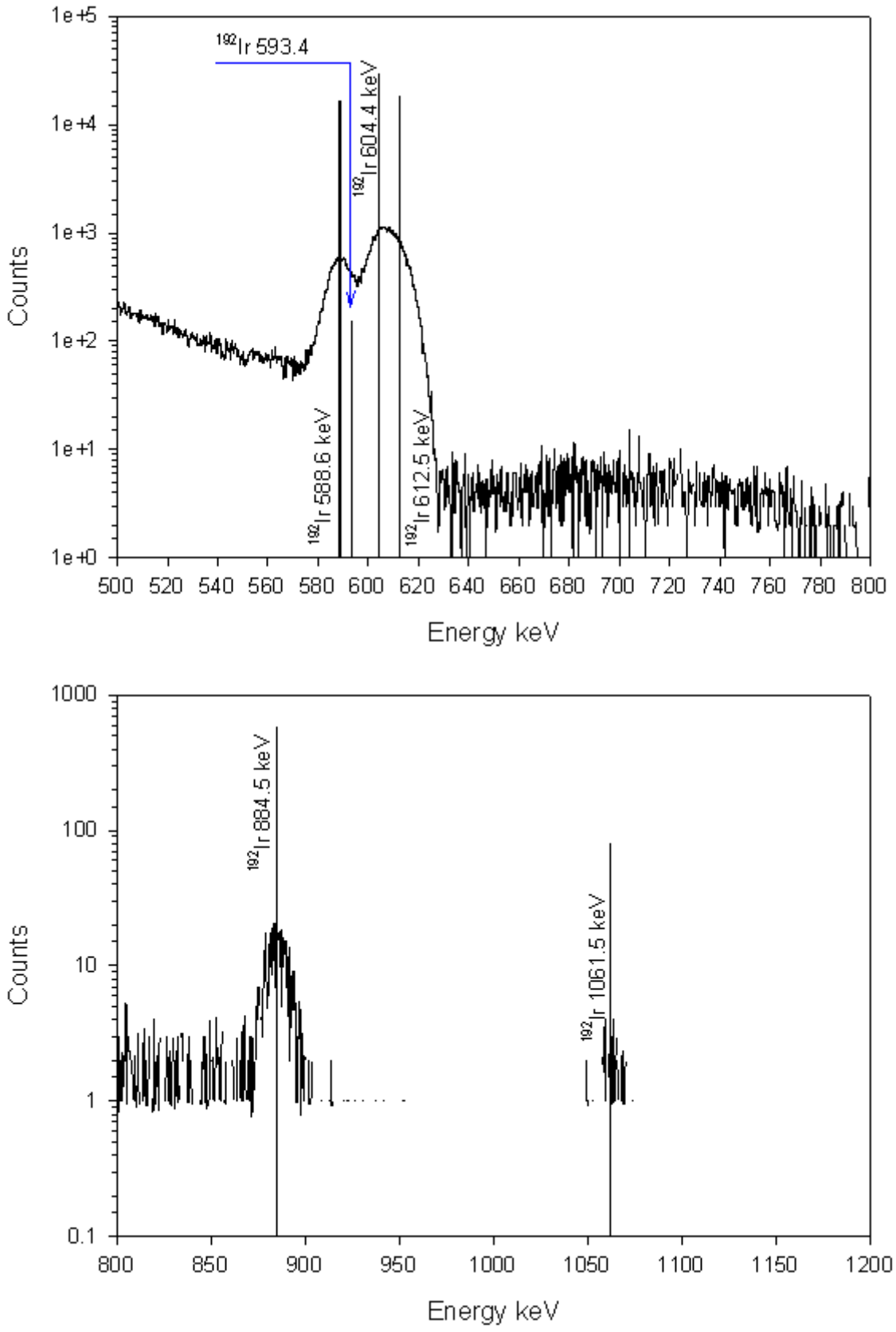


Figure A3. Assignation of constituent peaks for the spectrum of Scenario 3.

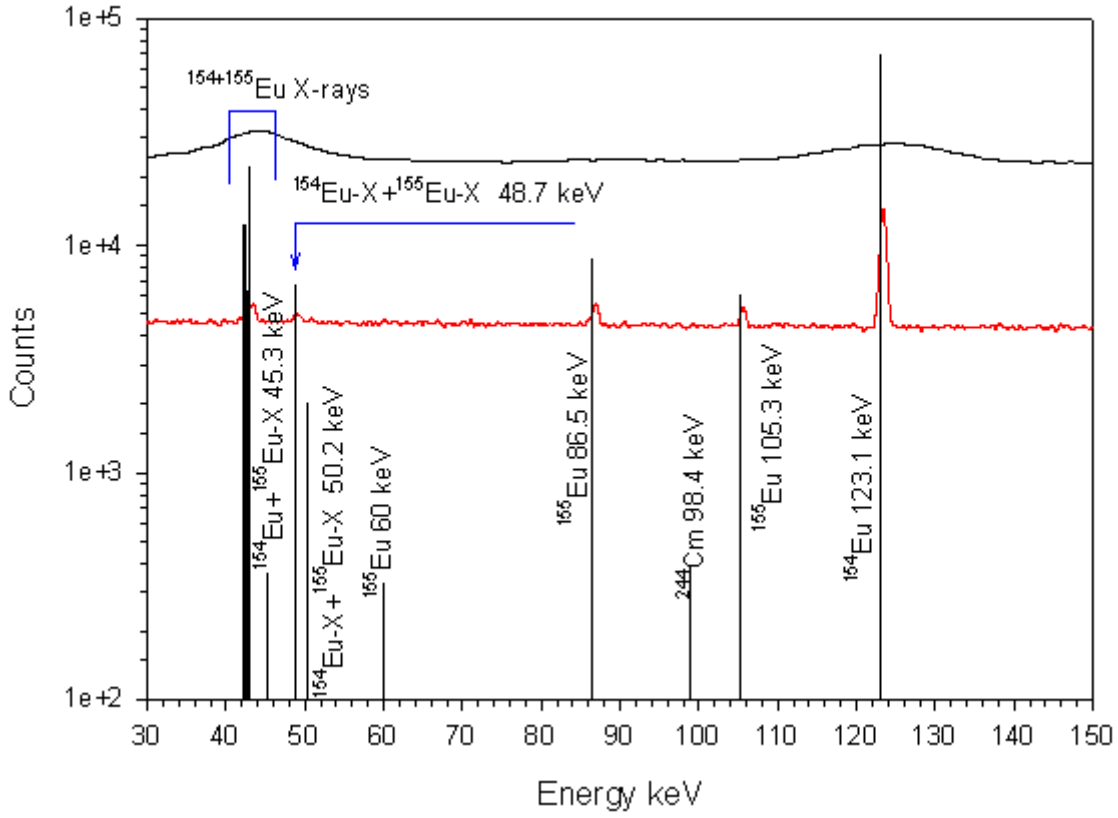
APPENDIX 4. Spectral information for Scenario 4.

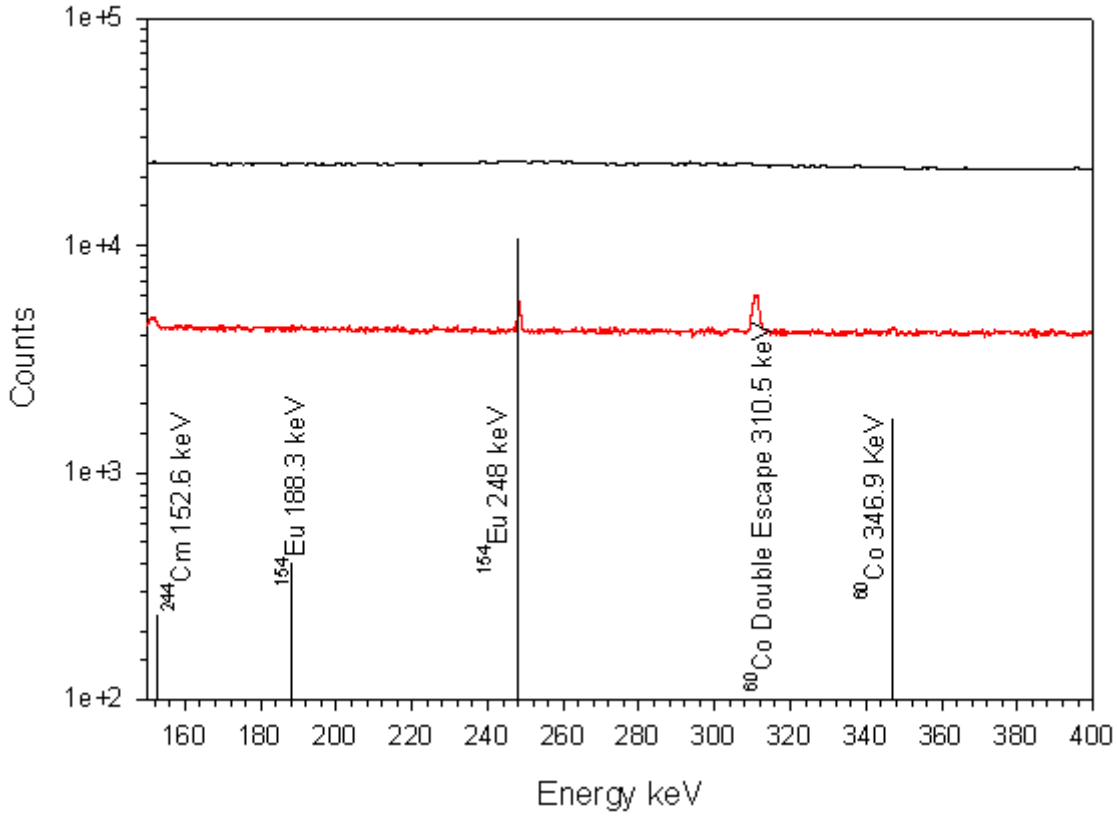
Nuclide	Energy keV	HPGe Channel	HPGe Counts	HPGe FWHM keV	NaI Channel	NaI Counts	NaI FWHM keV
Eu-155	42.3	106	139	0.9	27	1896.2	8.43
Eu-154	42.3	106	909	0.9	27	12401.7	8.43
Cm-244	42.8	108	488.6	0.9	27	6256	8.5
Eu-154	43	109	1784.2	0.9	27	22355.7	8.52
Eu-155	43	109	272.9	0.9	27	3419.4	8.52
Eu-155	45.3	116	36.6	0.9	29	356.9	8.8
Eu-154	48.7	127	911.1	0.9	32	6689.8	9.2
Eu-155	48.7	127	139.3	0.9	32	1022.5	9.2
Eu-155	50.2	132	47.1	0.9	33	310.4	9.38
Eu-154	50.2	132	307.9	0.9	33	2028.9	9.38
Eu-155	58	158	4.2	0.9	39	19	10.25
Eu-155	60	165	77.9	0.9	41	326.1	10.47
Eu-154	82	237	2.1	0.9	59	5.8	12.71
Eu-155	86.1	250	16.1	0.9	63	43	13.1
Eu-155	86.5	252	3273.1	0.9	63	8724.3	13.14
Cm-244	98.9	292	159.2	0.9	73	389.8	14.27
Eu-155	105.3	314	2556.9	0.9	78	6001.2	14.84
Eu-154	122.7	371	5.5	0.9	93	11.9	16.31
Eu-154	123.1	372	32039.8	0.9	93	69122.1	16.35
Eu-154	129.5	393	11	0.9	98	23.3	16.87
Eu-154	131.5	400	8.9	0.9	100	18.8	17.04
Eu-154	134.9	411	5.8	0.9	103	12.1	17.3
Eu-154	146	448	21	0.9	112	43	18.18
Eu-155	146.1	448	7	0.9	112	14.4	18.18
Cm-244	152.6	469	115.8	0.9	117	235.9	18.68
Eu-154	156.3	481	8.1	0.9	120	16.4	18.96
Eu-154	165.7	512	2	0.9	128	4.1	19.66
Eu-154	180.7	562	3.7	0.9	140	7.5	20.75
Eu-154	184.9	575	3.2	0.9	144	6.7	21.04
Eu-154	188.3	586	190.2	0.9	147	394.1	21.28
Eu-154	232.1	731	16.8	0.9	183	37.3	24.23
Eu-154	237.7	749	4.4	0.9	187	9.8	24.59
Eu-154	248	783	4687.5	0.9	196	10722.4	25.24
Cm-244	263.3	833	5.4	0.9	208	12.7	26.2
Eu-154	267.5	847	17.5	0.9	212	41.5	26.46
Eu-154	269.8	855	4.5	0.9	214	10.7	26.6
Eu-154	274	869	2.4	0.9	217	5.9	26.85
Eu-154	290	921	2	0.9	230	5.1	27.82
Eu-154	301.2	958	5.8	0.9	240	14.6	28.48
Eu-154	305.1	971	17.6	0.91	243	44.4	28.71
Eu-154	312.3	995	10.6	0.92	249	26.6	29.12
Eu-154	315.4	1005	4.2	0.93	251	10.4	29.3
Eu-154	322	1027	37.2	0.93	257	93.7	29.68
Eu-154	329.9	1053	5	0.95	263	12.5	30.13
Eu-154	346.6	1108	15.2	0.97	277	38.3	31.07
Co-60	346.9	1109	681.7	0.97	277	1717.9	31.08
Eu-154	370.8	1187	2.6	1	297	6.6	32.39
Eu-154	382	1224	4.8	1.02	306	12.1	33
Eu-154	397.2	1274	14	1.04	318	35.4	33.8
Eu-154	401.3	1287	96.4	1.04	322	243.9	34.02
Eu-154	403.5	1295	12.4	1.05	324	31.3	34.14
Eu-154	414.3	1330	2.2	1.06	333	5.6	34.7
Eu-154	444.5	1430	238.9	1.1	357	605.1	36.25
Eu-154	467.8	1506	24.7	1.13	377	62.5	37.42

Eu-154	478.3	1541	86.1	1.14	385	218.3	37.93
Eu-154	488.3	1573	2.8	1.15	390	5	38.2
Eu-154	506.5	1633	2.4	1.17	408	6.1	39.3
Eu-154	510.6	1647	22.6	1.18	412	57.3	39.5
Eu-154	512	1651	12.3	1.18	413	31.1	39.57
Eu-154	518	1671	17.7	1.19	418	44.8	39.86
Eu-154	533.1	1721	4.2	1.2	430	10.6	40.57
Eu-154	546.1	1764	5.1	1.22	441	13	41.18
Cm-244	554.5	1792	4.1	1.23	448	10.3	41.58
Eu-154	557.6	1802	89.6	1.23	450	226.8	41.72
Eu-154	569.2	1840	3.4	1.24	460	8.7	42.26
Eu-154	582.1	1882	302.7	1.26	471	765.3	42.84
Eu-154	591.8	1914	1667	1.27	479	4212.3	43.29
Cm-244	597.4	1932	2.2	1.27	483	5.5	43.54
Eu-154	598.2	1935	2.1	1.27	484	5.2	43.58
Eu-154	602.7	1950	12.3	1.28	487	31	43.78
Eu-154	613.3	1985	3.1	1.29	496	7.7	44.25
Eu-154	620.6	2009	3	1.3	502	7.5	44.58
Eu-154	625.3	2024	100.4	1.3	506	253	44.79
Eu-154	649.6	2104	22.2	1.33	526	55.8	45.86
Eu-154	651	2109	3.1	1.33	527	7.7	45.92
Cs-137	661.7	2144	37793.3	1.34	536	94978.8	46.39
Eu-154	664.7	2154	8.8	1.34	538	22.2	46.52
Eu-154	669.2	2169	4.1	1.35	542	10.2	46.71
Eu-154	676.6	2193	47.4	1.35	548	118.9	47.03
Eu-154	692.5	2245	497.3	1.37	561	1246.5	47.71
Eu-154	715.8	2322	54.2	1.39	581	135.5	48.71
Eu-154	723.4	2347	5745.6	1.4	587	14363.3	49.02
Eu-154	756.8	2457	1252.7	1.43	614	3122.7	50.42
Eu-154	774.4	2515	2.7	1.45	629	6.7	51.14
Eu-154	790.2	2567	2.9	1.46	642	7.2	51.78
Eu-154	800.7	2602	8.5	1.47	650	21	52.21
Eu-154	815.5	2650	133.3	1.49	663	330.5	52.81
Cm-244	817.9	2658	2.5	1.49	664	6.2	52.9
Co-60	826.1	2685	335.7	1.5	671	831.2	53.23
Eu-154	830.3	2699	2	1.5	675	5	53.4
Eu-154	845.4	2749	138.1	1.51	687	341.2	54
Eu-154	850.7	2766	57.3	1.52	691	141.4	54.21
Eu-154	873.2	2840	3003.4	1.54	710	7398.3	55.09
Eu-154	880.6	2864	20.9	1.55	716	51.5	55.38
Eu-154	892.8	2904	124.6	1.56	726	306.2	55.85
Eu-154	904.1	2942	213.8	1.57	735	524.9	56.29
Eu-154	906	2948	2.9	1.57	737	7	56.37
Eu-154	919.2	2991	2.9	1.58	748	7.2	56.88
Eu-154	924.6	3009	14.6	1.58	752	35.9	57.08
Eu-154	984.5	3206	2.1	1.63	802	5.1	59.35
Eu-154	996.3	3245	2337.1	1.64	811	5685.6	59.78
Eu-154	1004.8	3273	3942.9	1.65	818	9585.4	60.1
Eu-154	1033.4	3367	2.6	1.67	842	6.3	61.16
Eu-154	1047.2	3412	10.6	1.68	853	25.6	61.66
Eu-154	1049.4	3420	3.7	1.69	855	8.9	61.74
Eu-154	1118.3	3646	20.8	1.74	912	49.9	64.22
Eu-154	1128.5	3680	63.9	1.75	920	153.2	64.59
Eu-154	1140.8	3720	46.9	1.76	930	112.3	65.02
Eu-154	1153.1	3761	2.1	1.77	940	5.1	65.46
Eu-154	1160.5	3785	8.6	1.77	946	20.5	65.72
Co-60	1173.2	3827	3340736	1.78	957	7976131	66.16
Eu-154	1188.6	3877	15.6	1.79	969	37.3	66.7
Eu-154	1241.4	4051	24.2	1.83	1013	57.5	68.52
Eu-154	1246.2	4067	160.2	1.84	1017	380	68.68

Eu-154	1274.5	4160	6424.2	1.86	1040	15203	69.65
Eu-154	1290	4211	4.5	1.87	1053	10.6	70.17
Eu-154	1291.3	4216	2.3	1.87	1054	5.4	70.22
Eu-154	1316.4	4298	3.2	1.89	1075	7.5	71.06
Co-60	1332.5	4351	3015330	1.9	1088	7104517	71.6
Eu-154	1387	4530	3.4	1.94	1133	7.9	73.4
Eu-154	1408.3	4600	3.9	1.95	1150	9.1	74.1
Eu-154	1494	4883	111.8	2.01	1221	260.8	76.86
Eu-154	1537.9	5027	7.7	2.04	1257	17.9	78.25
Eu-154	1596.6	5220	274.5	2.08	1305	636.3	80.09
Eu-154	1673.6	5473	2.5	2.13	1368	5.7	82.46
Co-60	2158.6	7069	22.6	2.42	1767	51.5	96.56

Table A4. Comparison of NaI and HPGe spectra for the source of Scenario 4. (Note that escape peaks are not detailed in this list).

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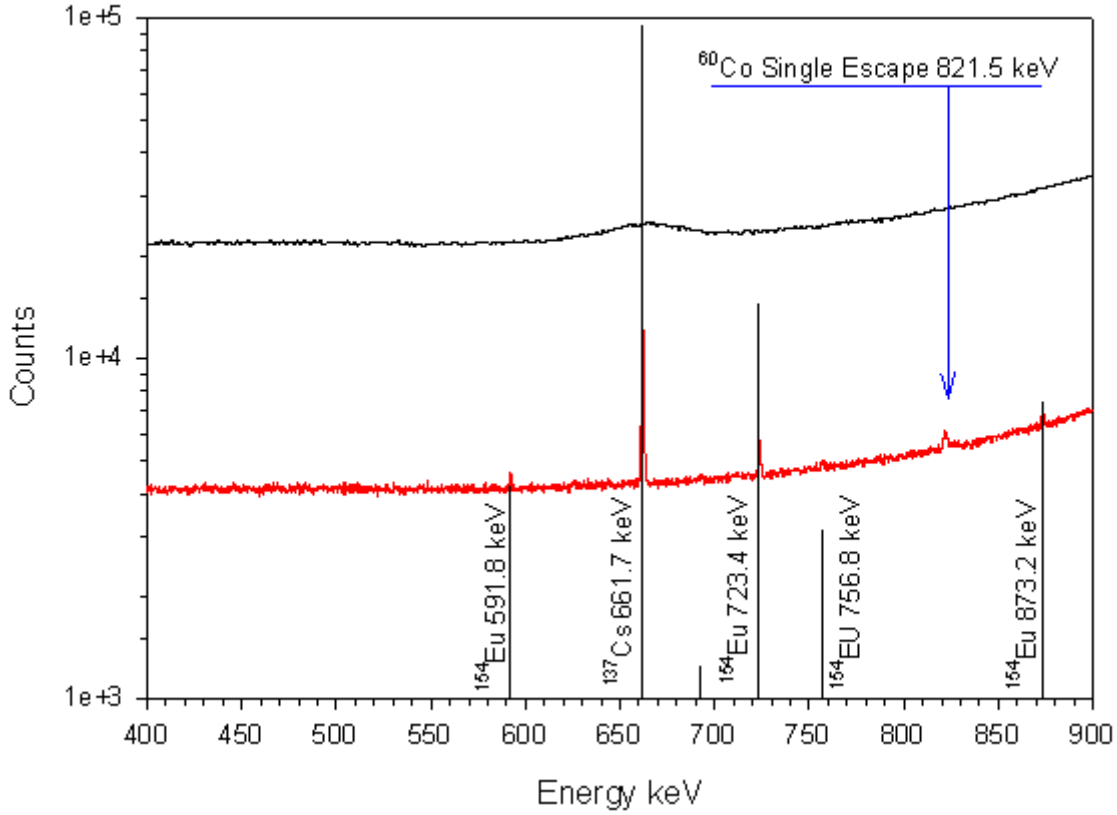
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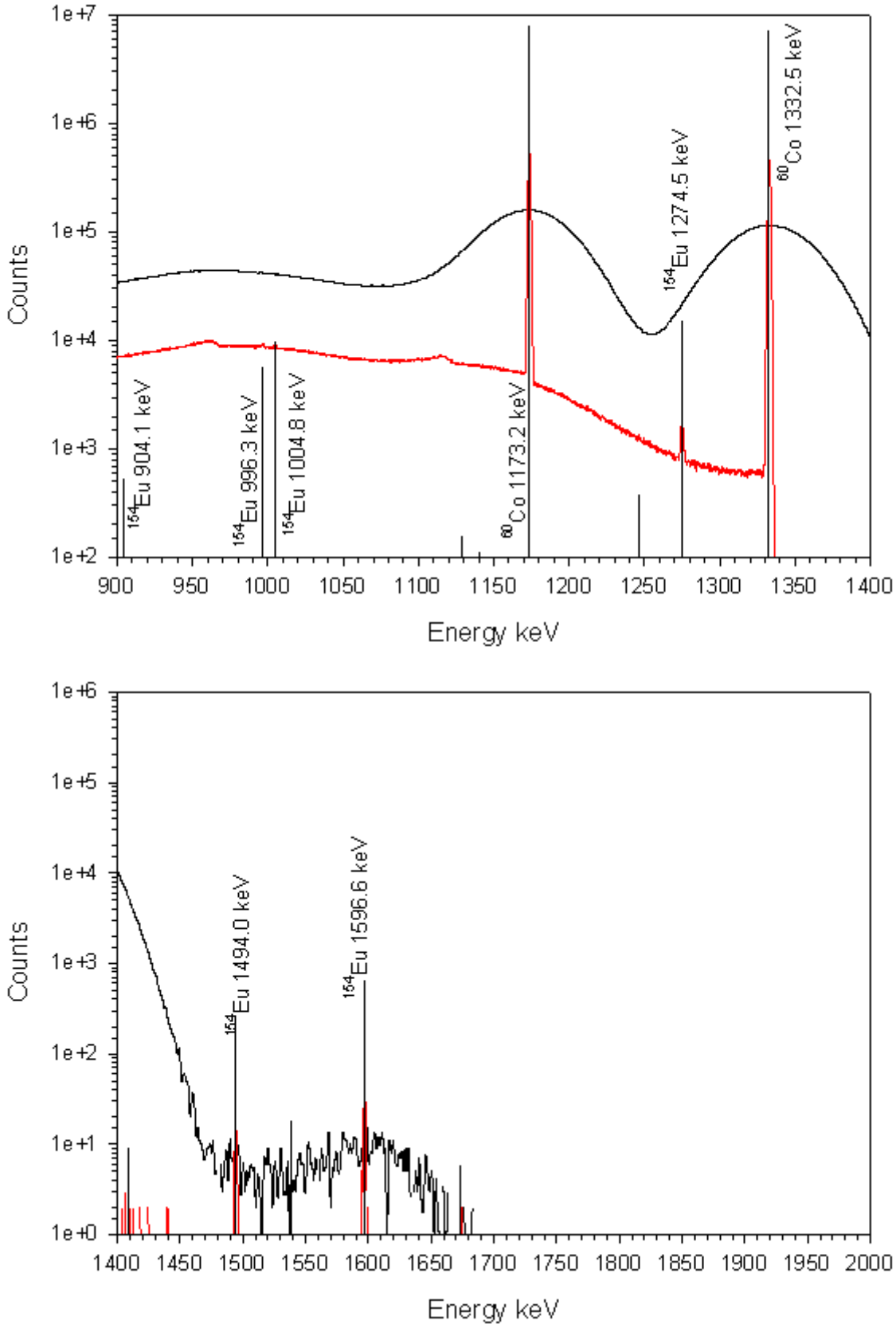
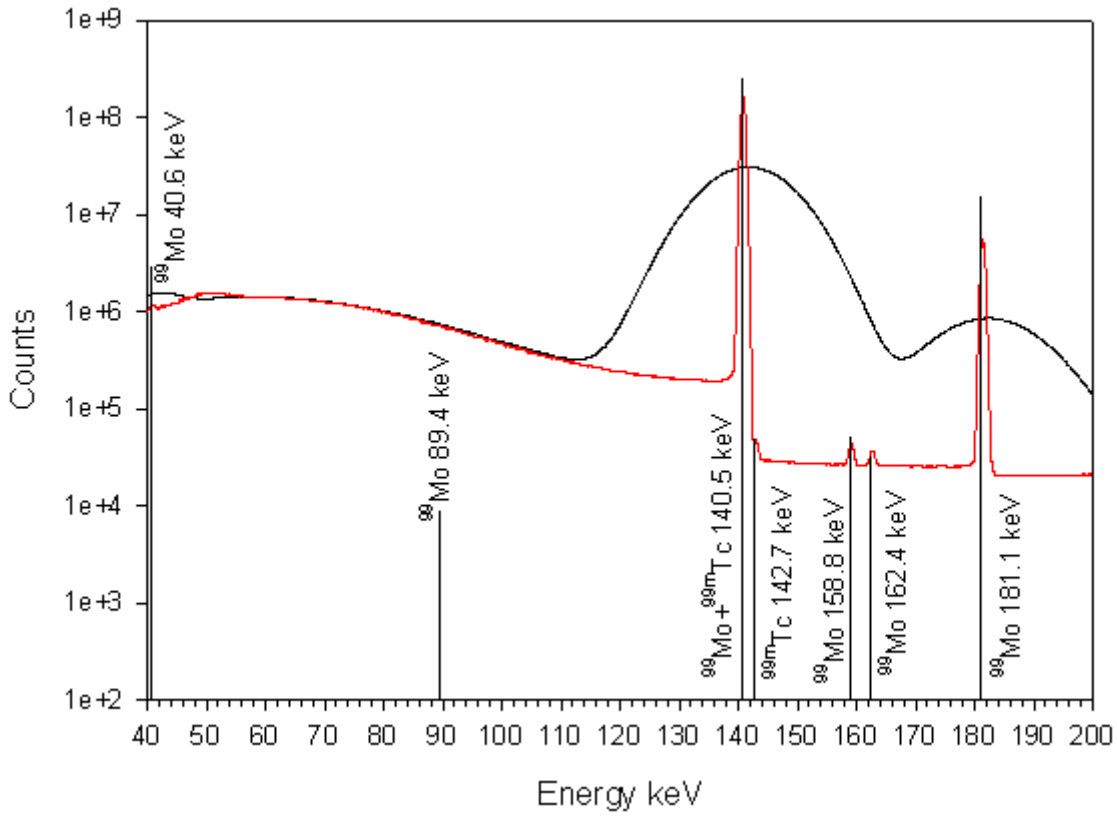


Figure A4. Assignation of constituent peaks for the spectrum of Scenario 4 (black) and the corresponding HPGe spectrum (red).

APPENDIX 5. Spectral information for Scenario 5.

Nuclide	Energy keV	Hpge Channel	HPGe Counts	HPGe FWHM keV	NaI Channel	NaI Counts	NaI FWHM keV
^{99}Mo	40.6	101	371192.6	0.9	25	2866771	8.22
^{99}Mo	89.4	261	7296.6	0.9	65	8655.9	13.41
^{99m}Tc	140.5	429	2.53E+08	0.9	107	2.34E+08	17.75
^{99}Mo	140.5	429	2.64E+08	0.9	107	2.44E+08	17.75
^{99m}Tc	142.7	436	53319.8	0.9	109	48918.7	17.92
^{99}Mo	158.8	490	56307	0.9	122	49798.1	19.15
^{99}Mo	162.4	501	35254.4	0.9	125	30976.5	19.41
^{99}Mo	181.1	563	17452450	0.9	141	14997570	20.77
^{99m}Tc	232.7	733	21.8	0.9	183	18.9	24.27
^{99}Mo	242.3	764	6268.9	0.9	191	5470.2	24.88
^{99}Mo	249.1	787	9625.2	0.9	197	8442.9	25.31
^{99m}Tc	322.4	1028	191.2	0.94	257	175.4	29.7
^{99}Mo	366.4	1173	2162337	1	293	1988443	32.16
^{99}Mo	380.1	1218	18325.2	1.02	304	16871	32.9
^{99}Mo	410.3	1317	3211.3	1.06	329	2953.3	34.49
^{99}Mo	411.5	1321	24037.3	1.06	330	22099.1	34.55
^{99}Mo	455.9	1467	2022.6	1.11	367	1838.7	36.82
^{99}Mo	457.6	1473	12233.7	1.11	368	11116.6	36.91
^{99}Mo	469.6	1512	3948.4	1.13	378	3577.5	37.51
^{99}Mo	528.7	1707	76404	1.2	427	68110.4	40.36
^{99}Mo	537.8	1736	4361	1.21	434	3876.7	40.79
^{99}Mo	580.5	1877	3973.4	1.25	469	3486.5	42.77
^{99}Mo	581.3	1880	1240.4	1.26	470	1088.2	42.81
^{99}Mo	620	2007	2715.6	1.3	502	2351.8	44.55
^{99}Mo	621.8	2013	30373.4	1.3	503	26287.2	44.63
^{99}Mo	739.5	2400	12404620	1.42	600	10310030	49.7
^{99}Mo	761.8	2473	399.1	1.44	618	329.3	50.62
^{99}Mo	777.9	2526	4181201	1.45	632	3433069	51.28
^{99}Mo	823	2675	124190.2	1.49	669	100424.9	53.11
^{99}Mo	861.2	2800	6338.2	1.53	700	5056	54.62
^{99}Mo	960.8	3128	84707.2	1.61	782	65380.1	58.45
^{99}Mo	986.4	3212	1085.8	1.64	803	831.4	59.42
^{99}Mo	1001.4	3262	4420.1	1.65	815	3369.9	59.97
^{99}Mo	1017	3313	484.2	1.66	828	367.1	60.55
^{99}Mo	1056.2	3442	748	1.69	861	559.1	61.99

Table A5. Comparison of HPGe and NaI spectra for the source of Scenario 5.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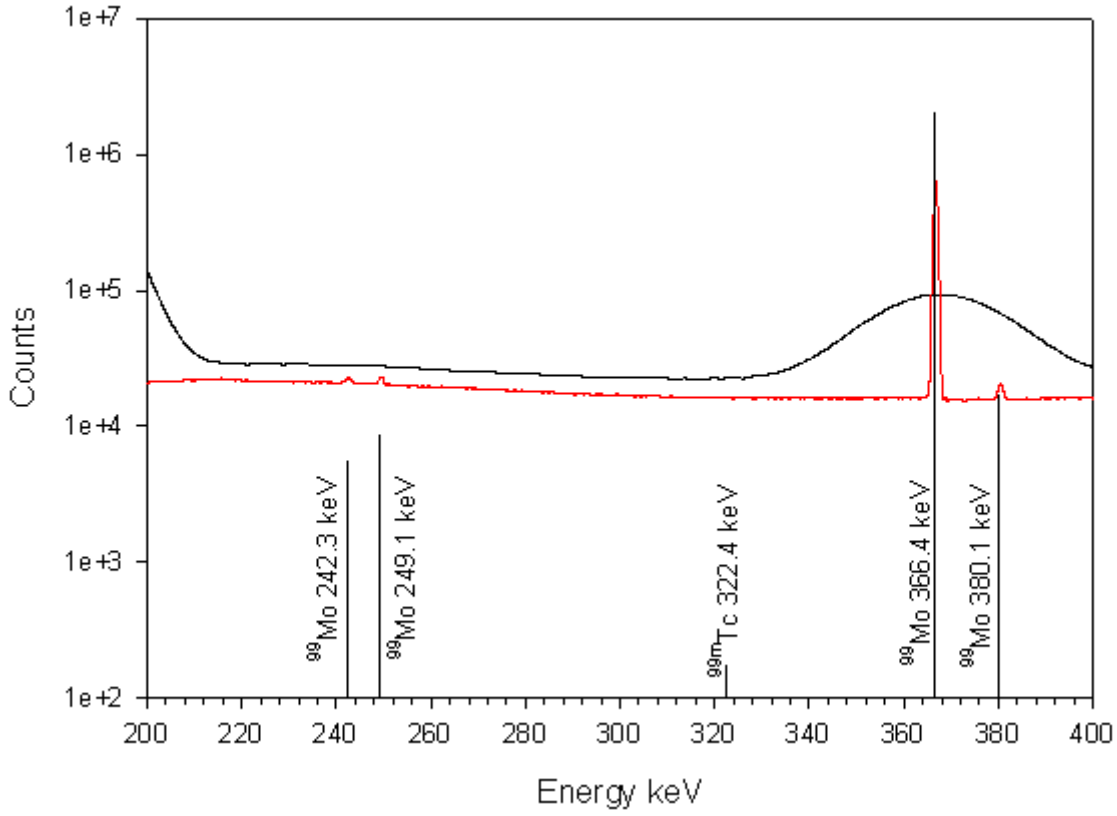
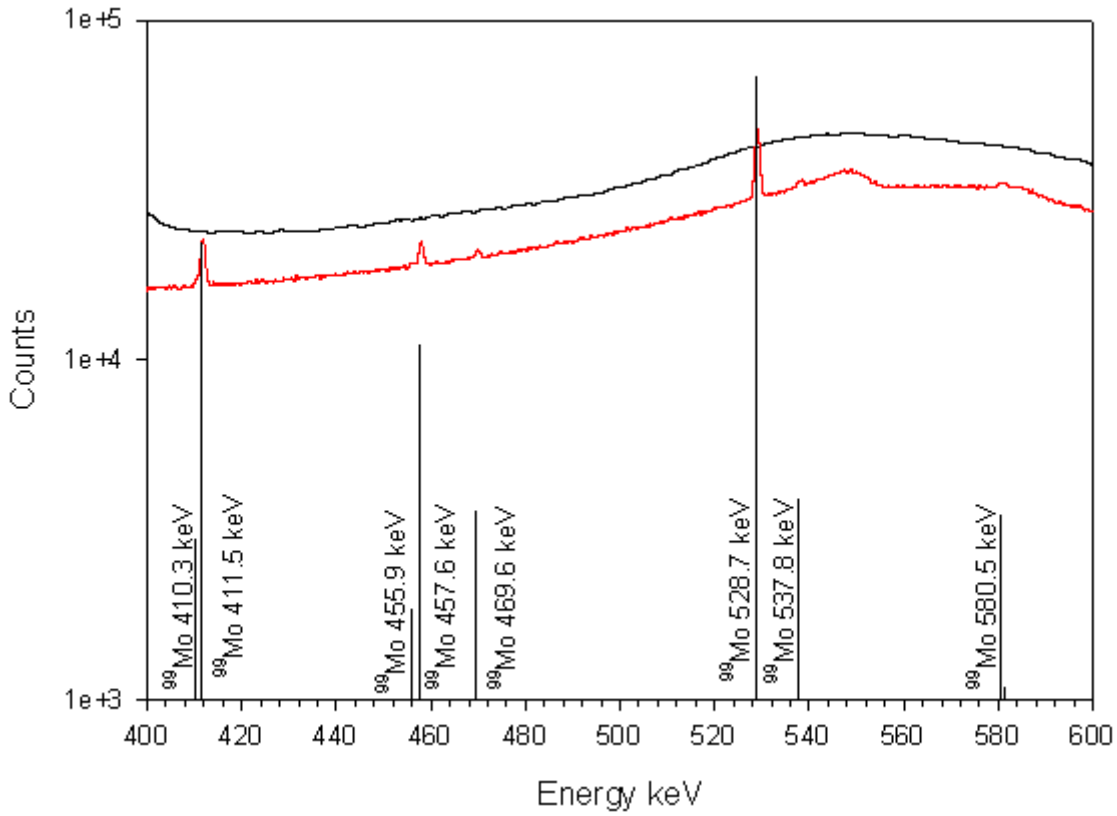
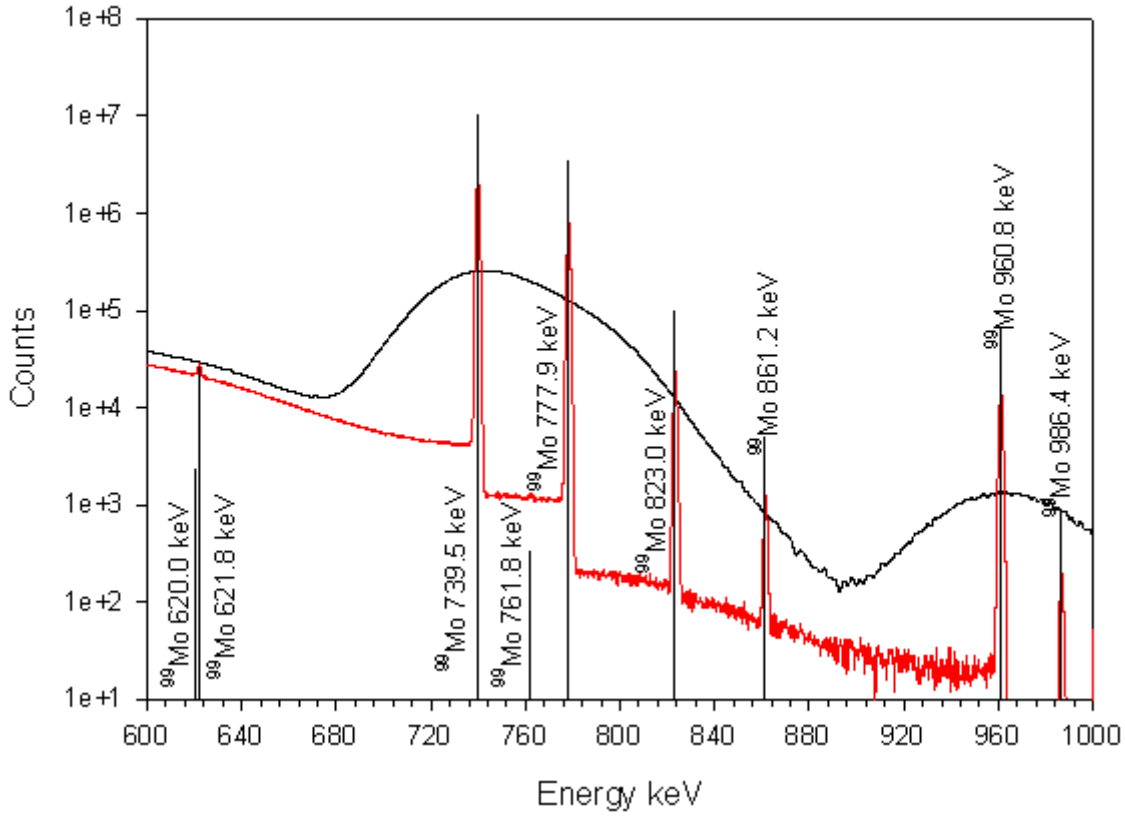
99Mo 158.8 keV
99Mo 162.4 keV
99Mo 181.1 keV


Counts
Energy keV
99Mo 242.3 keV
99Mo 249.1 keV
99mTc 322.4 keV
99Mo 366.4 keV
99Mo 380.1 keV


1e+5
1e+4
1e+3
Counts
400
420
440
460
480
500
520
540
560
580
600
Energy keV
99Mo 410.3 keV
99Mo 411.5 keV
99Mo 455.9 keV
99Mo 457.6 keV
99Mo 469.6 keV
99Mo 528.7 keV
99Mo 537.8 keV
99Mo 580.5 keV


1e+8
1e+7
1e+6
1e+5
1e+4
1e+3
1e+2
1e+1
Counts
600
640
680
720
760
800
840
880
920
960
1000
Energy keV
99Mo 620.0 keV
99Mo 621.8 keV
99Mo 739.5 keV
99Mo 761.8 keV
99Mo 777.9 keV
99Mo 823.0 keV
99Mo 861.2 keV
99Mo 960.8 keV
99Mo 986.4 keV

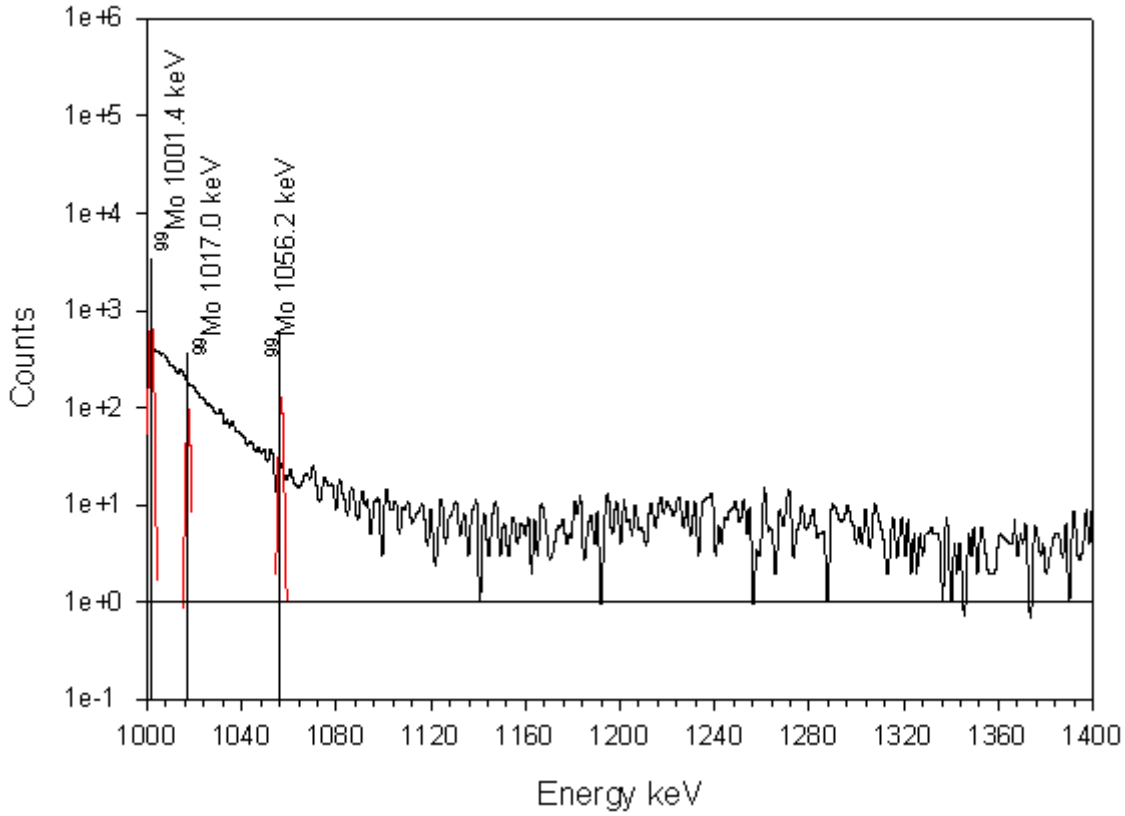
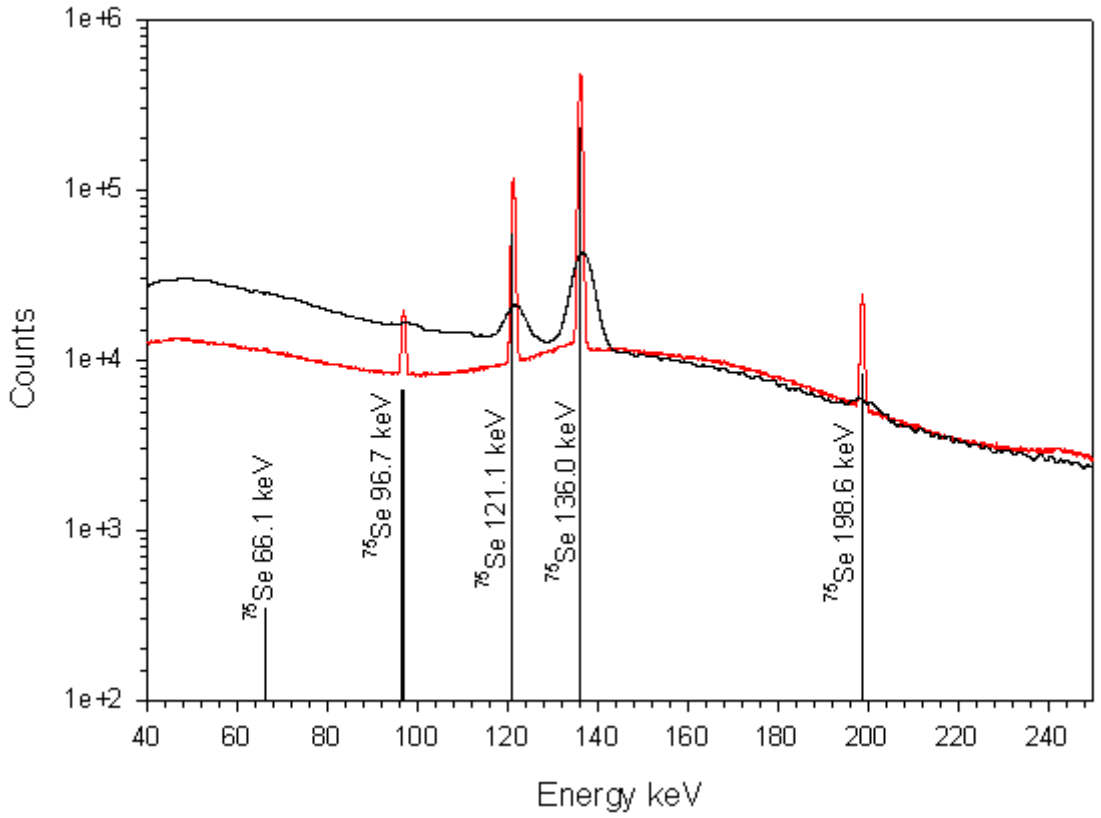


Figure A5. Assignation of constituent peaks for the spectrum of Scenario 5 (black) and associated HPGe spectrum (red).

APPENDIX 6 Spectral information for Scenario 6

Nuclide	Energy keV	Hpge Channel	HPGe Counts	HPGe FWHM keV	CdZnTe Channel	CdZnTe Counts	CdZnTe FWHM keV
^{75}Se	66.1	308	2177.8	0.9	77	346	3.57
^{75}Se	80.9	390	62.4	0.9	97	7.9	3.95
^{75}Se	96.7	477	60079.8	0.9	119	6631.4	4.32
^{75}Se	121.1	611	575209.9	0.9	153	55224.7	4.83
^{75}Se	136	693	2464185	0.9	173	228581.4	5.12
^{75}Se	198.6	1037	100678.3	0.9	259	8344.9	6.18
^{75}Se	264.7	1400	4531855	0.9	350	347884.2	7.14
^{75}Se	279.5	1482	1950445	0.92	370	148303.7	7.33
^{75}Se	303.9	1616	104579.3	0.96	404	7785.8	7.65
^{75}Se	373.6	1999	203.4	1.06	500	12.9	8.48
^{75}Se	400.7	2148	947582.2	1.1	537	56967.2	8.78
^{75}Se	419.1	2249	978.7	1.12	562	56.9	8.98
^{75}Se	572.2	3091	3022.5	1.31	773	138.4	10.49
^{75}Se	617.8	3342	378.6	1.36	835	16.3	10.9

Table A6. Constituent photopeaks for the spectrum of Scenario A6.



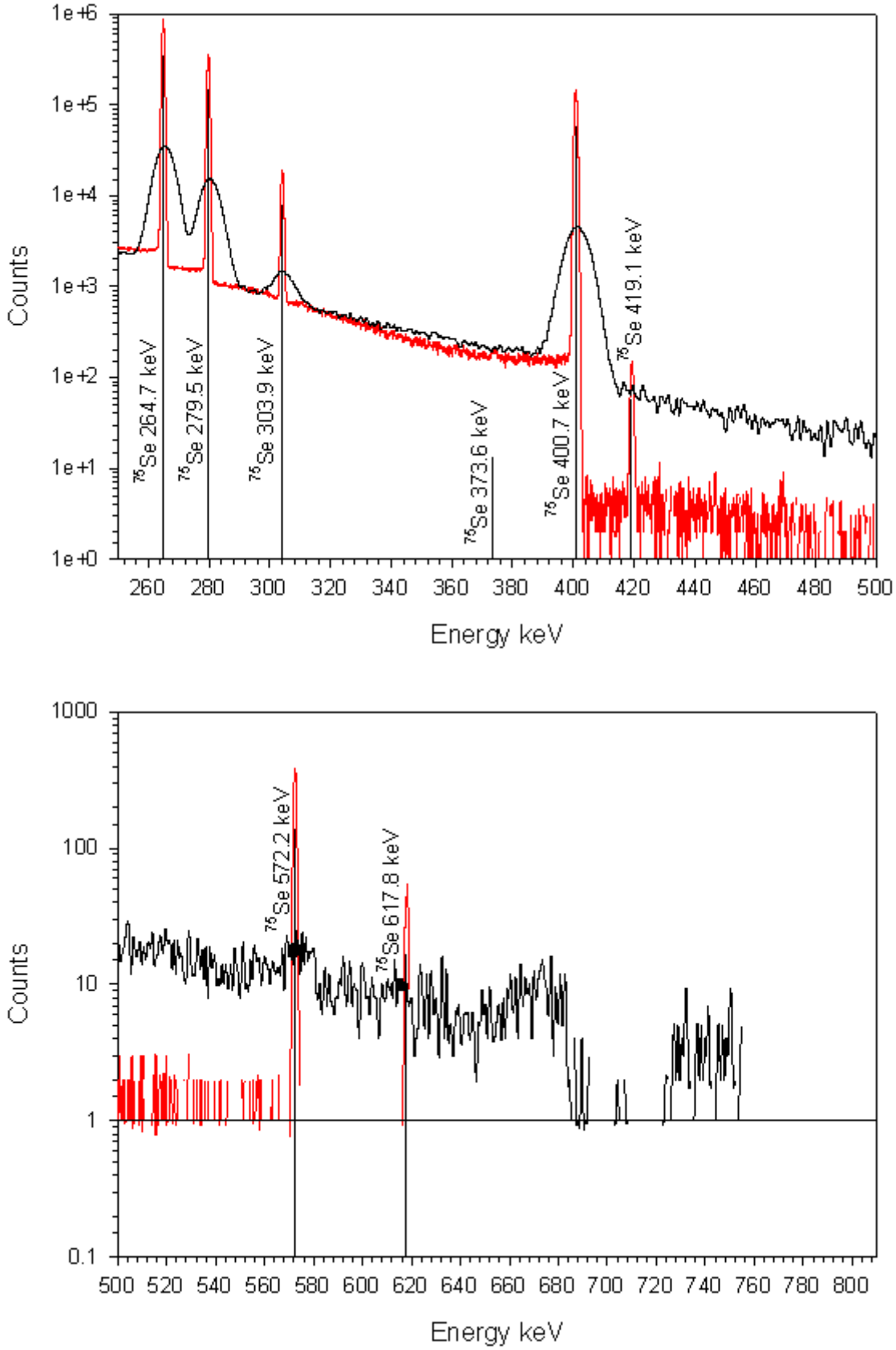


Figure A6. Assignation of constituent photopeaks for the spectrum of Scenario 6 (black) and the corresponding HPGe spectrum (red).

APPENDIX 7 Spectral information for Scenario 7

Channel	Energy keV	Area	Nuclide
59	31.6	24.5	U-235
68	34.7	156.1	U-235
82	39.9	1995	Bi-212
86	41.4	529.9	U-235
88	42	1158.7	U-235
88	42.2	1046.8	Th-231
89	42.4	3.2	U-233
90	42.8	1281.1	Th-231
93	44.1	18.5	Th-231
97	45.3	1062.4	Th-231
108	49.4	19009.3	U-236
108	49.6	92.8	U-238
113	51.2	1190	U-235
118	53.2	380278.1	U-234
121	54.1	2302.2	U-235
121	54.3	2331	U-235
122	54.7	2.6	U-233
131	57.8	20.4	Th-234
131	57.8	2758.9	U-232
133	58.6	51741.2	Th-231
144	62.7	20	Pa-234
144	62.7	4.8	Pa-234m
145	62.9	85.8	Th-234
146	63.3	20161.9	Th-234
147	63.8	3469.5	Th-231
149	64.4	1555.6	U-235
158	67.7	275.4	Th-230
160	68.5	1107.6	Th-231
167	70.8	2272.7	Bi-212
172	72.7	26209.2	U-235
172	72.8	59958.8	Th-231
172	72.8	24314.6	Tl-208
172	72.9	4108.5	Bi-212
175	73.9	124.1	Th-234
175	73.9	93.2	Pa-234m
175	74	308.8	Th-234
178	74.8	15677.3	U-235
178	74.8	368045.1	Pb-212
178	75	44918.6	Tl-208
183	76.9	1563.4	Bi-212
184	77.1	680674	Pb-212
184	77.3	4.5	Pa-231
190	79.3	2886.8	Bi-212
195	81.1	5797.6	Ra-224
195	81.2	299997.2	Th-231
198	82.1	139058.6	Th-231
199	82.6	1434.8	Bi-212
201	83.3	822.3	Th-234
202	83.8	10622.9	Ra-224
203	84.2	2470221	Th-231
204	84.4	62073.3	Th-228
204	84.5	7668.3	Tl-208
206	85.1	1096.1	Bi-212
207	85.4	969.6	Th-228

208	85.8	2288	Th-231
210	86.8	115221.5	Pb-212
211	87	223.6	Th-234
212	87.3	5894.3	Tl-208
212	87.3	224686.1	Pb-212
213	87.7	69.4	Pa-231
215	88.5	1757.5	Th-228
218	89.6	2119	Bi-212
219	89.9	420974.6	Th-231
219	90	2689311	U-235
219	90	2643.3	U-236
219	90.1	22745.3	Pb-212
222	90.9	124.6	Pa-231
225	92.3	201451.7	Th-231
225	92.3	6882.9	Th-234
226	92.4	38794.1	Th-234
227	92.7	1056.1	Bi-212
227	92.8	38696.1	Th-234
228	93.1	22074.4	Th-231
228	93.4	28.3	U-233
228	93.4	5437955	U-235
228	93.4	4761.8	U-236
231	94.2	1740.2	Ra-224
232	94.7	2089.3	Pa-234m
232	94.7	760.9	Pa-234
233	94.9	3378.8	Ra-224
235	95.9	364932	Th-231
235	95.9	12140.2	Th-234
236	96.1	45748.8	U-235
238	96.8	10.9	Pa-231
239	97.1	19.5	U-233
239	97.2	12.4	Pa-234
240	97.5	1357.7	Ra-224
240	97.6	12701.7	Th-231
242	98.4	3701.6	Pa-234m
242	98.4	1346.6	Pa-234
245	99.3	69106.4	Th-231
245	99.4	2853.1	Th-228
246	99.9	176.5	Pa-234
249	100.8	3.8	Pa-231
249	100.9	7	Pa-234
253	102.3	251746.9	Th-231
254	102.8	39.3	Pa-231
255	102.9	223.5	Th-228
256	103.4	76.1	Th-234
257	103.8	14.5	Pa-234
260	104.8	846895.8	U-235
262	105.6	8.8	U-233
262	105.6	1589100	U-235
262	105.8	4719.3	Th-231
263	106.1	13	Pa-231
265	106.6	11477.1	Th-231
265	106.7	2.3	Pa-234
265	106.9	20361.4	Th-231
269	108	211.1	Th-234
270	108.4	111932.2	Th-231
270	108.4	3613.3	Th-234
270	108.6	599.9	U-236
270	108.6	3.5	U-233
270	108.6	6315304	U-235

271	109	2332260	U-235
271	109	211.9	U-236
272	109.2	1092333	U-235
275	110.4	58	Pa-234m
277	111	640.3	Pa-234
278	111.3	1135.3	Pa-234m
278	111.5	1485.4	Th-234
278	111.5	45846.7	Th-231
279	111.9	16086.8	Th-231
282	112.8	70561	U-236
282	112.8	6011.8	Th-234
284	113.5	223.9	U-238
286	114.4	463.2	Pa-234m
287	114.9	230	Pa-234
288	115.2	62948.1	Pb-212
289	115.5	17141.3	U-235
289	115.6	245.7	Th-231
293	116.8	5238.2	Th-231
302	120.4	7131	U-235
304	120.9	412868.2	U-234
313	124.1	1288.1	Bi-212
315	124.9	16965.2	Th-231
316	125.5	22.6	Pa-234
326	129.1	3049.3	U-232
332	131.3	586.1	Pa-234
333	131.6	6116.8	Th-228
340	134	8707.1	Th-231
341	134.6	3.9	Pa-234
344	135.7	29175.5	Th-231
347	136.6	4559	U-235
347	136.7	1599.8	Th-231
357	140.1	19.1	Pa-234
357	140.1	14.8	Pa-234m
358	140.5	289.1	Th-231
358	140.8	89896.5	U-235
367	143.8	13	Pa-234
367	143.8	4708553	U-235
367	143.9	82.3	Th-230
367	144	582.9	Bi-212
370	145.1	2543.1	Th-231
372	145.9	14217.6	Th-231
374	146.3	5.3	U-233
383	149.9	3.2	Pa-234
386	150.9	36399.9	U-235
391	152.7	278.6	Pa-234
410	159.5	33	Pa-234
420	163.1	87045.8	Th-231
420	163.4	2861479	U-235
422	164	383.7	Bi-212
423	164.5	6.7	U-233
425	164.9	2.8	Pa-234
425	165	2238.1	Th-231
426	165.6	3.9	Pa-234
429	166.4	8169.8	Th-228
437	169.6	724.7	Th-231
441	170.9	28.9	Pa-234
447	173	25003.2	Th-231
447	173.3	6269.4	U-235
450	174.2	11590.8	Th-231
451	174.6	9.9	Pa-234

457	176.7	4553	Pb-212
465	179.8	2.8	Pa-234
466	180.2	289.2	Bi-212
473	182.5	231823.8	U-235
475	183.5	22600.3	Th-231
479	184.7	33.7	Pa-234m
479	184.8	225.2	Th-234
481	185.7	40054400	U-235
482	186.1	24.2	Th-230
483	186.2	116.8	Pa-234
488	187.9	2.4	U-233
490	188.8	2291	Th-231
497	191.4	3.1	U-232
501	192.9	11.8	Pa-234m
501	192.9	3.2	Pa-234m
503	193.7	34.3	Pa-234
507	194.9	471137.3	U-235
512	196.8	5.1	Pa-234
518	198.9	32203.5	U-235
519	199.6	76999.5	U-235
520	200	12.5	Pa-234m
520	200	5.3	Pa-234
523	201	65.9	Pa-234
526	202.1	841497.6	U-235
529	203.1	91	Pa-234
529	203.2	22.8	Pa-234m
535	205.3	3955969	U-235
537	205.9	2098.5	Th-228
543	208.2	3.3	U-233
548	209.9	30	Pa-234m
552	211.4	6989.4	Tl-208
562	215.3	22075.7	U-235
564	216	28150.3	Th-228
568	217.2	4.7	U-233
570	217.9	32972.1	Th-231
575	220	11.3	Pa-234
579	221.2	4	Pa-234
579	221.4	99855.5	U-235
580	221.8	5.7	Pa-234
593	226.5	334.4	Pa-234
595	227.3	462.5	Pa-234
599	228.5	2.1	Th-228
599	228.8	6772.6	U-235
609	232.2	14.1	Pa-234
612	233.4	12749.6	Tl-208
612	233.5	24776.1	U-235
617	235.1	9.1	Pa-234
619	236	7892.3	Th-231
624	237.8	77435.2	Th-231
626	238.6	5044498	Pb-212
631	240.2	4.2	Pa-234
631	240.2	241.8	Th-231
633	240.9	64817.4	U-235
633	241	479260.8	Ra-224
636	242.1	8.8	Pa-231
637	242.5	727.6	Th-231
639	243.2	8.6	Pa-231
640	243.5	12.4	Pa-234m
645	245.4	5.6	U-233
645	245.4	61.6	Pa-234

646	245.9	2	Pa-231
649	246.9	46146.1	U-235
651	247.8	6.1	Pa-234m
654	248.7	2.2	U-233
655	249.2	206.2	Pa-234
656	249.6	680.9	Th-231
659	250.4	567.8	Th-231
662	251.5	34977.7	U-235
665	252.6	29370.7	Tl-208
668	253.7	38.1	Th-230
668	253.9	2.9	Th-230
673	255.8	20.8	Pa-231
677	257.2	4.2	Pa-234
680	258.2	1823.8	Pa-234m
685	260.2	34.9	Pa-231
703	266.5	5291.4	U-235
704	267.1	14.2	Pa-234
706	267.6	1023.3	Th-231
713	270.3	378.1	U-232
719	272.3	90.1	Pa-234
721	273.2	11.1	Pa-231
724	274.1	26.5	Th-231
726	275	7.8	Pa-234
726	275	7.8	Pa-234m
726	275.1	37086.9	U-235
732	277.3	12.9	Pa-231
732	277.4	271024.6	Tl-208
735	278.3	3.4	Pa-234
738	279.5	238373.1	U-235
744	281.4	5297.5	U-235
748	282.9	4413.6	U-235
750	283.7	317.1	Pa-231
762	288.1	36965.6	Bi-212
766	289.6	6169.3	U-235
771	291.4	8.5	U-233
772	291.7	3347.3	U-235
775	292.7	738	Ra-224
778	293.8	248.6	Pa-234
779	294.3	29040.4	U-235
781	295.1	2854.7	Bi-212
783	295.9	12	Pa-234
792	299.1	16	Pa-234m
795	300.1	457	Pa-231
795	300.1	389138.8	Pb-212
799	301.7	4383.6	U-235
802	302.6	125.9	Pa-231
802	302.7	407.4	Pa-231
819	308.7	340.5	Th-231
822	310.2	5.9	Pa-234
823	310.5	2.2	Pa-234m
824	310.7	3487.7	U-235
825	311	2528.3	Th-231
830	312.9	18.8	Pa-231
832	313.5	8.5	Pa-234
840	316.7	4.5	Pa-234m
840	316.7	8.5	Pa-234
841	317.1	867.9	U-235
842	317.2	12	U-233
844	317.9	69.4	Th-231
850	320.2	95.2	Th-231

850	320.4	4.2	Pa-234
851	320.5	4.5	U-233
869	327.1	6.9	Pa-231
871	328	16168	Bi-212
871	328	330	U-232
877	330.1	253.3	Pa-231
878	330.4	62.5	Pa-234
881	331.4	5.8	Pa-234
883	332.4	48.7	U-232
899	338.1	27.2	Pa-234m
900	338.3	4.3	U-232
905	340.2	3.2	Pa-234
906	340.7	32.5	Pa-231
914	343.5	2542.2	U-235
915	343.8	2.7	Pa-234
919	345.4	59202.7	U-235
920	345.9	32127.8	U-235
937	351.8	58.8	Th-231
937	351.9	32.5	Pa-234
944	354.5	17.7	Pa-231
948	356.1	4180.7	U-235
951	357.1	30.9	Pa-231
952	357.5	18.8	Pa-234m
953	357.9	2.8	Pa-234
967	362.8	16.1	Pa-234m
982	368.5	57709.2	U-235
985	369.5	192.3	Pa-234
991	371.8	5748.6	U-235
992	372	94.7	Pa-234
1000	374.9	8.5	Pa-231
1011	379.1	3.2	Pa-234
1012	379.4	8.7	Pa-231
1029	385.4	3.1	Pa-234
1035	387.6	21.8	Pa-234m
1035	387.9	30613	U-235
1035	387.9	10.7	Pa-234m
1042	390.3	32121	U-235
1052	394.1	7	Pa-234
1062	397.7	2	Pa-234
1073	401.8	2.7	Pa-234
1080	404.2	234.7	Ra-224
1090	407.8	6	Pa-231
1095	409.8	25.2	Pa-234
1097	410.3	2349.4	U-235
1110	415.2	15042.9	Pb-212
1113	416.1	2.6	Pa-234
1138	425.3	2.6	Pa-234
1142	427	32.6	Pa-234
1142	427	11.3	Pa-231
1159	433.1	6.7	Pa-234
1161	433.6	1233.2	Bi-212
1196	446.6	8	Pa-234
1201	448.4	745.6	U-235
1208	450.9	63.6	Pa-234m
1213	452.8	31080	Bi-212
1215	453.6	40.1	Pa-234m
1219	455	803.5	U-234
1220	455.1	5913.1	U-235
1224	456.7	14.9	Pa-234m
1229	458.6	78.6	Pa-234

1237	461.5	2.4	Pa-234
1244	464.2	2.1	Pa-234
1255	468	14.8	Pa-234
1255	468.1	47.7	Pa-234m
1267	472.3	24.7	Pa-234
1270	473.6	4489.2	Bi-212
1272	474.2	2.5	Pa-234
1276	475.8	47	Pa-234m
1284	478.7	8.4	Pa-234
1290	481	20.9	Pa-234
1304	486	1723.6	Tl-208
1323	492.7	571.5	Bi-212
1337	498	4.1	Pa-234
1352	503.5	28.7	U-234
1361	506.7	84.4	Pa-234
1363	507.5	30.8	Pa-234m
1365	508.2	440.5	U-234
1368	509.2	41.3	Pa-234m
1372	510.8	756608.2	Tl-208
1379	513.4	84.3	Pa-234
1390	517.2	273.2	U-235
1396	519.6	25.1	Pa-234
1401	521.4	47.5	Pa-234
1419	527.9	24.8	Pa-234
1422	529.1	5.7	Pa-234
1436	534.1	5.2	Pa-234
1444	537.2	5.2	Pa-234
1463	543.8	8.4	Pa-234
1463	544	67.7	Pa-234m
1479	549.8	10116.3	Rn-220
1490	553.7	2.7	Pa-234
1499	557.3	13.2	Pa-234m
1501	558	5.7	Pa-234
1505	559.2	4.4	Pa-234
1515	562.8	2.2	Pa-234
1521	565.2	62.7	Pa-234
1531	568.9	218.2	Pa-234
1533	569.5	496.7	Pa-234
1540	572	11.1	Pa-234m
1551	576	68	Bi-212
1567	581.8	329.6	U-234
1570	583.2	2591216	Tl-208
1573	584.1	10.4	Pa-234
1579	586.3	4.3	Pa-234
1583	587.8	1218.1	Tl-208
1590	590.3	2.1	Pa-234
1604	595.4	5.5	Pa-234
1608	596.9	11.5	Pa-234
1624	602.6	31.5	Pa-234
1629	604.6	3	Pa-234
1649	612	21.9	Pa-234
1663	617	2.9	Pa-234
1669	619	2.1	Pa-234
1672	620.4	294.3	Bi-212
1683	624.2	19.9	Pa-234
1683	624.4	20.9	U-234
1687	625.7	2.4	Pa-234m
1693	628.1	13.6	Pa-234
1697	629.4	19.8	Pa-234
1706	632.6	2	Pa-234

1710	634.3	7.5	Pa-234
1741	645.5	429.5	Ra-224
1744	646.5	6.3	Pa-234
1747	647.7	26.1	Pa-234m
1751	649	17	Pa-234m
1754	650.1	1022.6	Tl-208
1764	653.7	25.3	Pa-234
1768	655.2	7.4	Pa-234
1768	655.3	22.9	Pa-234m
1774	657.4	21.4	Pa-234
1780	659.8	14.7	Pa-234
1792	663.9	29.4	Pa-234
1799	666.5	63	Pa-234
1807	669.7	53.6	Pa-234
1810	670.8	6	Pa-234m
1819	673.9	10.4	Pa-234m
1822	675.1	5.4	Pa-234
1829	677.7	24.7	U-234
1845	683.4	9.2	Pa-234m
1846	683.9	8	Pa-234
1850	685.1	7.5	Pa-234
1866	691.1	124.7	Pa-234m
1870	692.6	65.6	Pa-234
1878	695.5	24.8	Pa-234m
1888	699	189.2	Pa-234
1895	701.6	112	Pa-234m
1905	705.2	589.8	Tl-208
1907	705.9	63	Pa-234m
1907	705.9	118.8	Pa-234
1922	711.5	8	Pa-234
1928	713.7	7.5	Pa-234
1951	722	5310.4	Tl-208
1965	727.3	480913	Bi-212
1967	727.8	5.8	Pa-234
1975	730.9	32.1	Pa-234
1980	732.5	19.8	Pa-234m
1982	733.4	350.4	Pa-234
1995	738	58.1	Pa-234
2000	740	178.2	Pa-234m
2007	742.5	213	U-235
2008	742.8	1214.9	Pa-234m
2008	742.8	103.8	Pa-234
2016	745.9	16.1	Pa-234
2022	748.1	5.2	Pa-234
2024	748.7	1107.1	Tl-208
2041	755	60.7	Pa-234
2052	758.9	12.2	Pa-234
2056	760.3	23.3	Pa-234m
2058	761	3.6	Pa-234
2063	763.1	45962.2	Tl-208
2068	764.8	9.9	Pa-234
2072	766.4	3.4	Pa-234
2072	766.4	4365.4	Pa-234m
2080	769.1	9.1	Pa-234
2089	772.4	3.5	Pa-234
2106	778.6	2.2	Pa-234
2111	780.4	43.7	Pa-234
2113	781.4	113.9	Pa-234m
2119	783.4	14.5	Pa-234
2124	785.4	76225	Bi-212

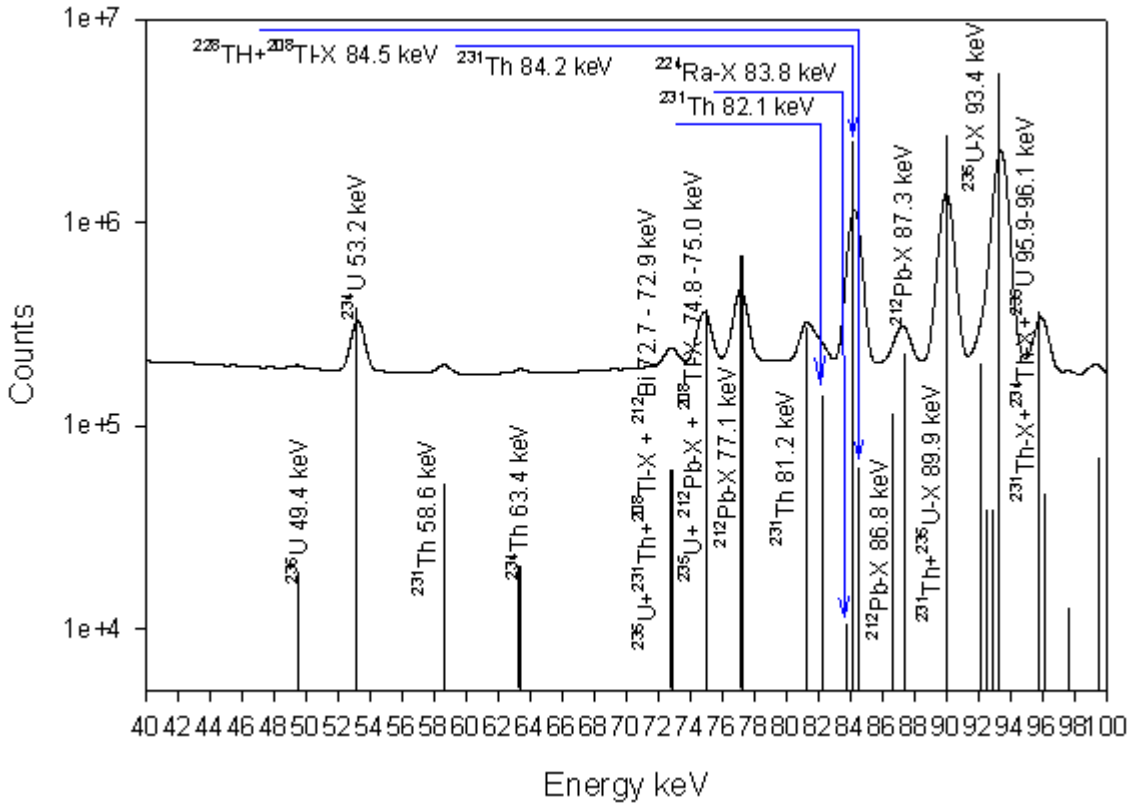
2127	786.3	57.7	Pa-234
2127	786.3	707	Pa-234m
2145	792.8	2.1	Pa-234
2150	794.7	304.3	U-235
2150	794.9	67.1	Pa-234
2154	796.1	123.5	Pa-234
2176	804.4	29.5	Pa-234
2181	805.9	119.6	Pa-234
2181	805.9	61.6	Pa-234m
2187	808.3	42.9	Pa-234m
2192	809.9	7266.4	Pa-234m
2196	811.5	5.8	Pa-234
2203	814.2	14.6	Pa-234
2214	818.2	14.2	Pa-234m
2217	819.2	88.1	Pa-234
2222	821.1	961.6	Tl-208
2231	824.2	5.8	Pa-234
2233	825.1	87.7	Pa-234
2235	825.6	19.7	Pa-234m
2245	829.3	16.7	Pa-234
2251	831.5	191.1	Pa-234
2285	844.1	19.3	Pa-234
2285	844.1	15	Pa-234m
2291	846.1	2.3	Pa-234
2306	851.7	3.3	Pa-234
2306	851.7	85.3	Pa-234m
2330	860.6	289037.6	Tl-208
2338	863.2	3.2	Pa-234
2347	866.8	14.4	Pa-234m
2355	869.7	8.8	Pa-234
2373	876	112.7	Pa-234
2385	880.5	177.9	Pa-234
2385	880.5	266.8	Pa-234
2387	881.1	36.2	Pa-234m
2392	883.2	15.7	Pa-234m
2393	883.2	426	Pa-234
2393	883.2	22.8	Pa-234m
2393	883.3	706.4	Tl-208
2404	887.3	94.5	Pa-234m
2420	893.4	23799.9	Bi-212
2435	898.7	141.9	Pa-234
2450	904.4	14.8	Pa-234
2489	918.4	4.3	Pa-234
2498	921.7	164.7	Pa-234m
2507	925	334.5	Pa-234
2509	925.9	77.1	Pa-234
2512	926.7	15.9	Pa-234m
2512	926.7	308.4	Pa-234
2514	927.4	2885	Tl-208
2537	935.8	2.8	Pa-234
2538	936.3	23.1	Pa-234m
2553	941.9	31.8	Pa-234m
2564	946	565.2	Pa-234
2564	946	126	Pa-234m
2569	947.7	68.2	Pa-234
2581	952.1	10212	Bi-212
2583	952.7	3.4	Pa-234
2603	960	11.3	Pa-234m
2603	960	3	Pa-234
2619	965.8	19.5	Pa-234

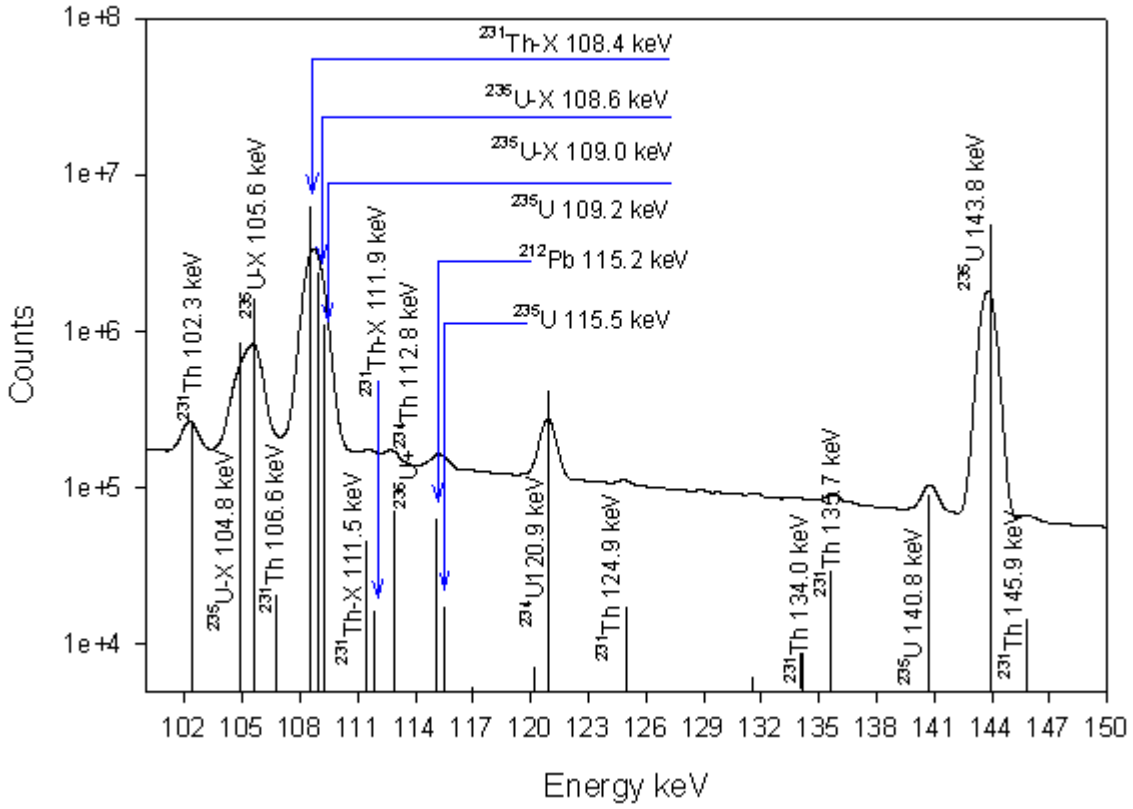
2653	978.2	3.7	Pa-234
2658	980.3	123.2	Pa-234
2658	980.3	82.2	Pa-234
2662	981.6	29.5	Pa-234
2665	982.7	4282.8	Tl-208
2669	984.2	66.3	Pa-234
2683	989.2	4.2	Pa-234
2690	992	3.3	Pa-234
2698	994.6	251.9	Pa-234
2702	996.1	50.2	Pa-234m
2715	1001	10195.8	Pa-234m
2740	1009.9	2.6	Pa-234
2772	1021.8	5.6	Pa-234
2782	1025.3	2	Pa-234
2791	1028.7	22.5	Pa-234
2827	1041.7	14.2	Pa-234m
2834	1044.4	11.7	Pa-234
2853	1051.4	2.4	Pa-234
2875	1059.4	12.7	Pa-234m
2882	1061.9	26.7	Pa-234m
2914	1073.6	3.9	Pa-234
2915	1074.1	865.9	Bi-212
2928	1078.7	30798	Bi-212
2940	1083.2	10.2	Pa-234m
2940	1083.2	19	Pa-234
2946	1085.4	5.5	Pa-234m
2970	1093.9	7770.7	Tl-208
3005	1106.9	3.1	Pa-234
3015	1110.6	2.3	Pa-234
3043	1120.6	19	Pa-234m
3047	1122.1	18.5	Pa-234
3055	1125.2	13.3	Pa-234
3057	1125.7	94.8	Tl-208
3057	1125.7	39	Pa-234m
3060	1126.8	11.1	Pa-234
3060	1126.8	5.9	Pa-234m
3133	1153.6	10.9	Pa-234
3153	1160.8	204.2	Tl-208
3182	1171.3	3.2	Pa-234
3190	1174.2	20.5	Pa-234m
3220	1185.1	310.6	Tl-208
3243	1193.7	143.5	Pa-234m
3243	1193.8	7.4	Pa-234
3308	1217.3	7.5	Pa-234
3316	1220.4	9.4	Pa-234m
3316	1220.4	2.2	Pa-234
3362	1237.2	54.8	Pa-234m
3373	1241.2	7.8	Pa-234
3415	1256.5	20	Pa-234
3487	1282.8	893.4	Tl-208
3515	1292.8	15.3	Pa-234
3535	1300.1	339.8	Bi-212
3679	1352.9	36.8	Pa-234
3680	1353	6	Pa-234m
3684	1354.6	4.2	Pa-234
3696	1359	4.9	Pa-234
3757	1381.1	113.4	Tl-208
3780	1389.6	2.3	Pa-234
3786	1391.9	32.5	Pa-234m
3792	1393.9	64.4	Pa-234

3801	1397.5	2.6	Pa-234
3809	1400.3	5.4	Pa-234
3847	1414	21.4	Pa-234m
3882	1426.9	5.1	Pa-234
3905	1435.4	89.2	Pa-234m
3933	1445.4	9.7	Pa-234
3953	1452.7	24.2	Pa-234
3969	1458.5	16.4	Pa-234m
3970	1458.9	2.8	Pa-234
4065	1493.6	3	Pa-234
4085	1501	11.5	Pa-234m
4111	1510.5	11.4	Pa-234m
4117	1512.8	12135.2	Bi-212
4125	1515.6	2.1	Pa-234
4157	1527.2	20.9	Pa-234m
4219	1550	10.2	Pa-234m
4220	1550.1	2.1	Pa-234
4231	1554.1	69.7	Pa-234m
4242	1558.3	6.5	Pa-234m
4276	1570.7	9.4	Pa-234m
4301	1579.9	2	Pa-234
4318	1585.9	4.1	Pa-234
4340	1593.9	22.8	Pa-234m
4340	1594	8.7	Pa-234
4361	1601.8	4	Pa-234m
4412	1620.5	58922.9	Bi-212
4431	1627.3	2.1	Pa-234
4461	1638.1	5.6	Pa-234
4486	1647.5	28	Tl-208
4541	1667.6	6.7	Pa-234m
4544	1668.4	20.5	Pa-234
4574	1679.5	2	Pa-234
4575	1679.7	2224.9	Bi-212
4591	1685.7	8.3	Pa-234
4613	1693.8	18.4	Pa-234
4614	1694.1	3.6	Pa-234m
4617	1695	7.2	Pa-234
4632	1700.5	2.7	Pa-234
4686	1720.5	2.5	Pa-234m
4706	1727.8	52.3	Pa-234
4718	1732.2	14.2	Pa-234m
4734	1737.8	165.9	Pa-234m
4751	1744	26.7	Tl-208
4794	1759.8	10.9	Pa-234m
4810	1765.4	67.3	Pa-234m
4894	1796.2	2.4	Pa-234m
4896	1797.1	6	Pa-234
4921	1806	3244.4	Bi-212
4929	1809	28	Pa-234m
4958	1819.7	6.8	Pa-234m
4991	1831.5	129.2	Pa-234m
5077	1863.1	8.9	Pa-234m
5090	1867.7	67.8	Pa-234m
5110	1875.2	60.2	Pa-234m
5151	1890.1	3.5	Pa-234
5160	1893.5	15.9	Pa-234m
5169	1896.7	2.5	Pa-234
5209	1911.2	45.4	Pa-234m
5248	1925.4	7.1	Pa-234
5251	1926.4	2.2	Pa-234m

5280	1937	20.7	Pa-234m
5370	1970	3.9	Pa-234m
7136	2614.5	910710.4	Tl-208

Table A7. Constituent photopeaks for the spectrum of Scenario 7. (Note that escape peaks are not included in the list).




Counts
Energy keV
231Th-X 108.4 keV
235U-X 108.6 keV
235U-X 109.0 keV
235U 109.2 keV
212Pb 115.2 keV
235U 115.5 keV
231Th 102.3 keV
235U-X 104.8 keV
235U-X 105.6 keV
231Th 106.6 keV
231Th-X 111.5 keV
231Th-X 111.9 keV
234Th 112.8 keV
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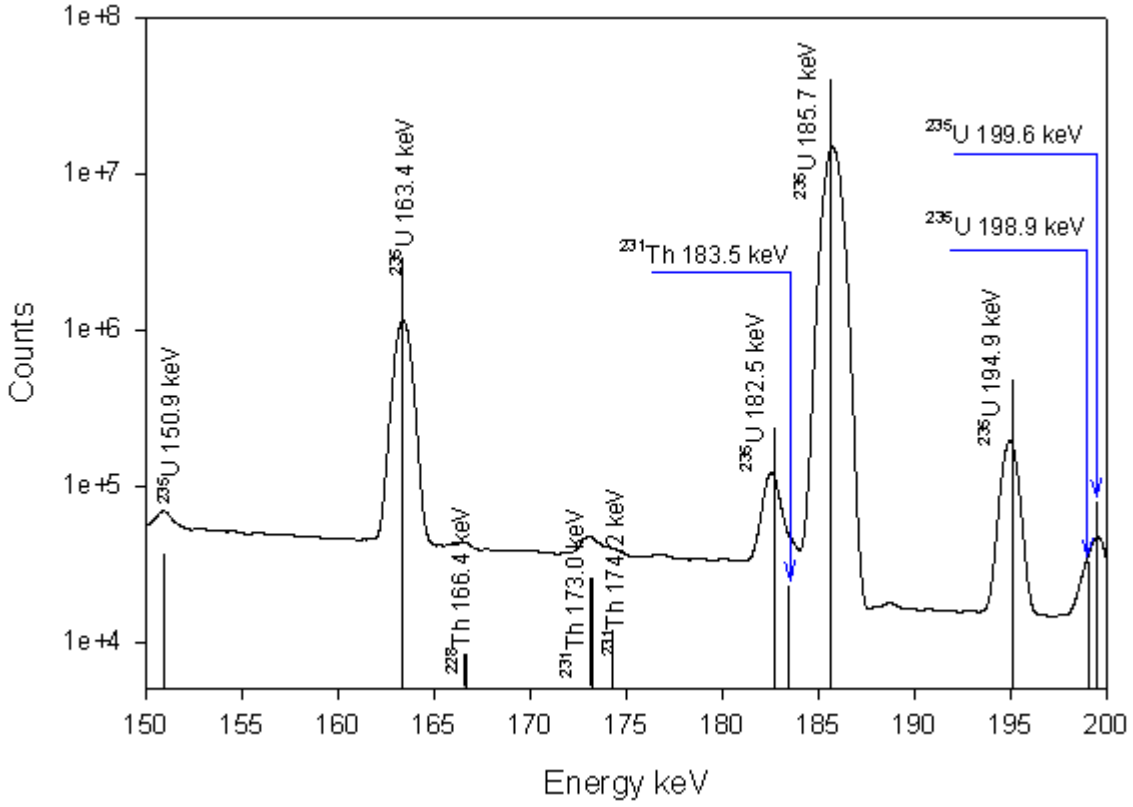
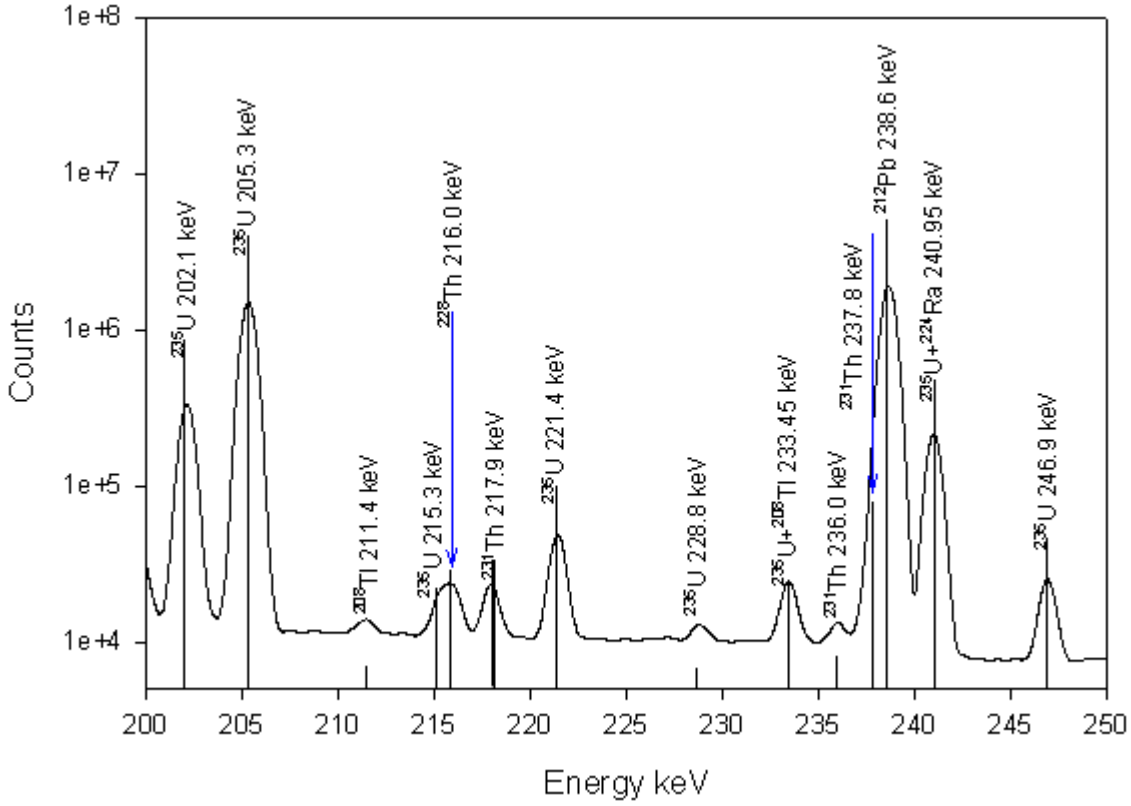
231Th 135.7 keV
235U 140.8 keV
235U 143.8 keV
231Th 145.9 keV


Counts
Energy keV
235U 150.9 keV
235U 163.4 keV
228Th 166.4 keV
231Th 173.0 keV
231Th 174.2 keV
231Th 183.5 keV
235U 182.5 keV
235U 185.7 keV
235U 194.9 keV
235U 198.9 keV
235U 199.6 keV


Counts
Energy keV
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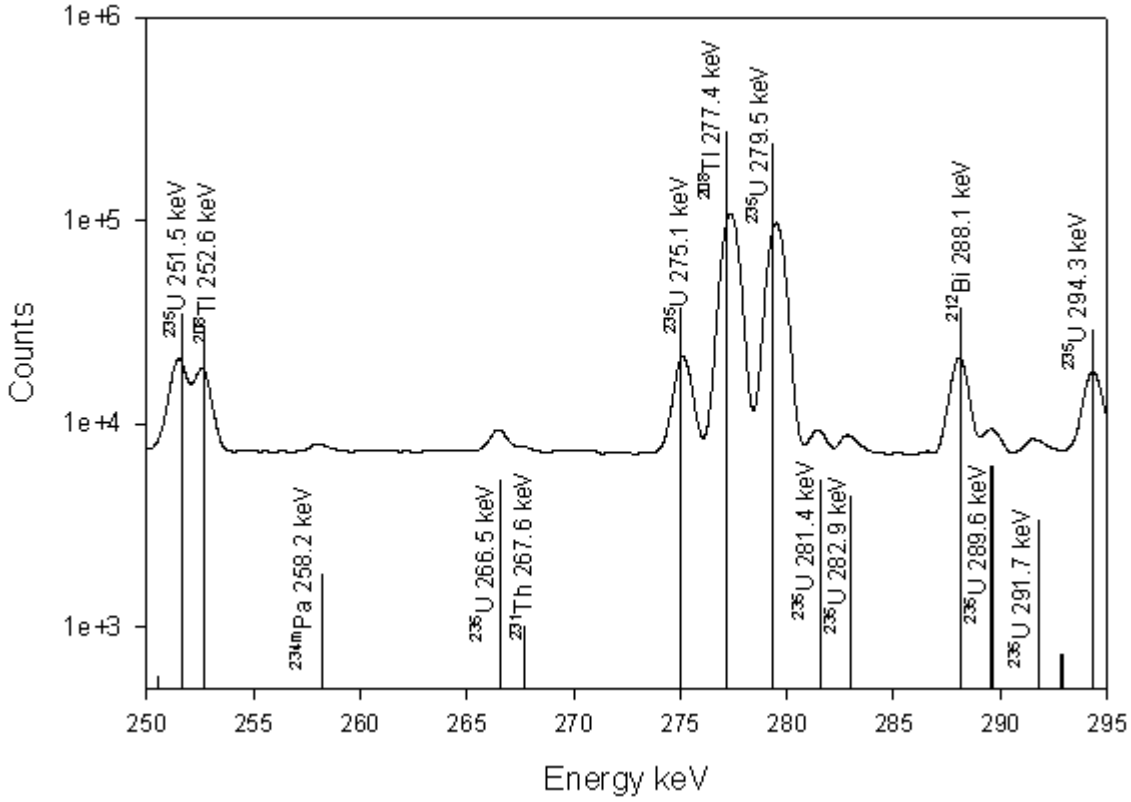
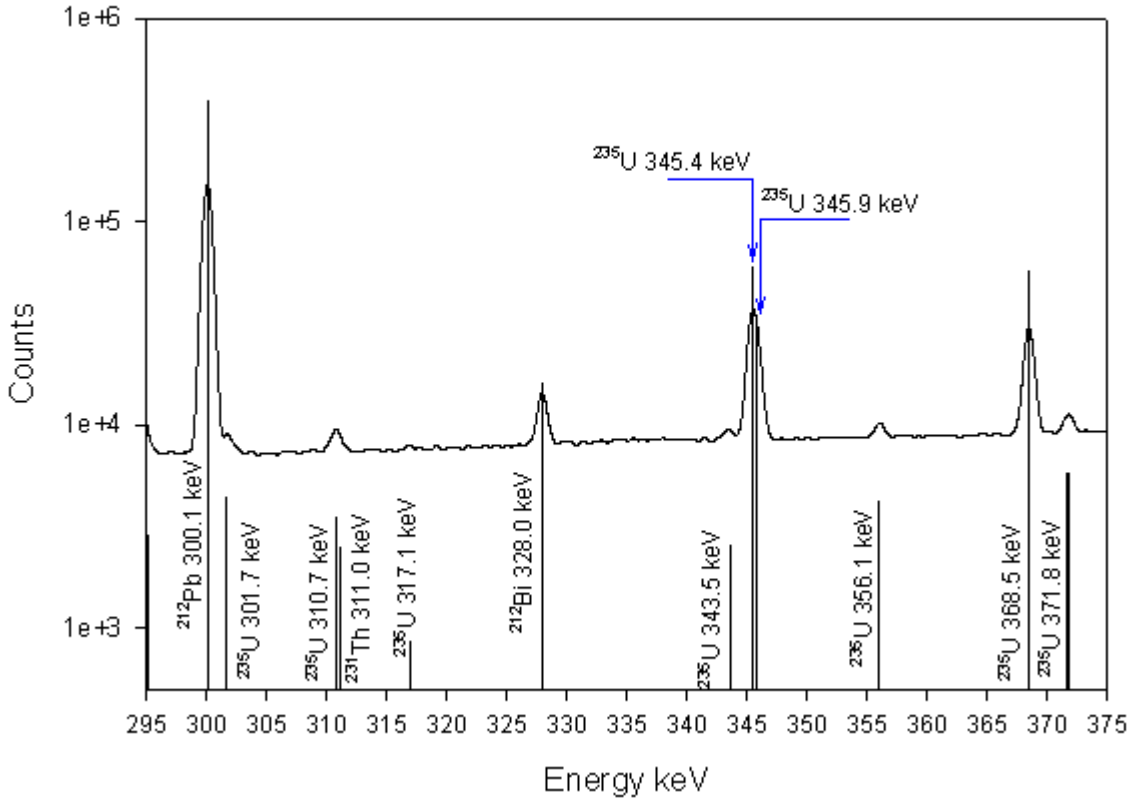
1e+7
1e+6
1e+5
1e+4
200
205
210
215
220
225
230
235
240
245
250
235U 202.1 keV
235U 205.3 keV
208Tl 211.4 keV
235U 215.3 keV
228Th 216.0 keV
231Th 217.9 keV
235U 221.4 keV
235U 228.8 keV
235U+208Tl 233.45 keV
231Th 236.0 keV
231Th 237.8 keV
212Pb 238.6 keV
235U+224Ra 240.95 keV
235U 246.9 keV


Counts
Energy keV
1e+6
1e+5
1e+4
1e+3
250
255
260
265
270
275
280
285
290
295
235U 251.5 keV
208Tl 252.6 keV
234mPa 258.2 keV
235U 266.5 keV
231Th 267.6 keV
235U 275.1 keV
208Tl 277.4 keV
235U 279.5 keV
235U 281.4 keV
235U 282.9 keV
212Bi 288.1 keV
235U 289.6 keV
235U 291.7 keV
235U 294.3 keV


Counts
Energy keV
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1e+5
1e+4
1e+3
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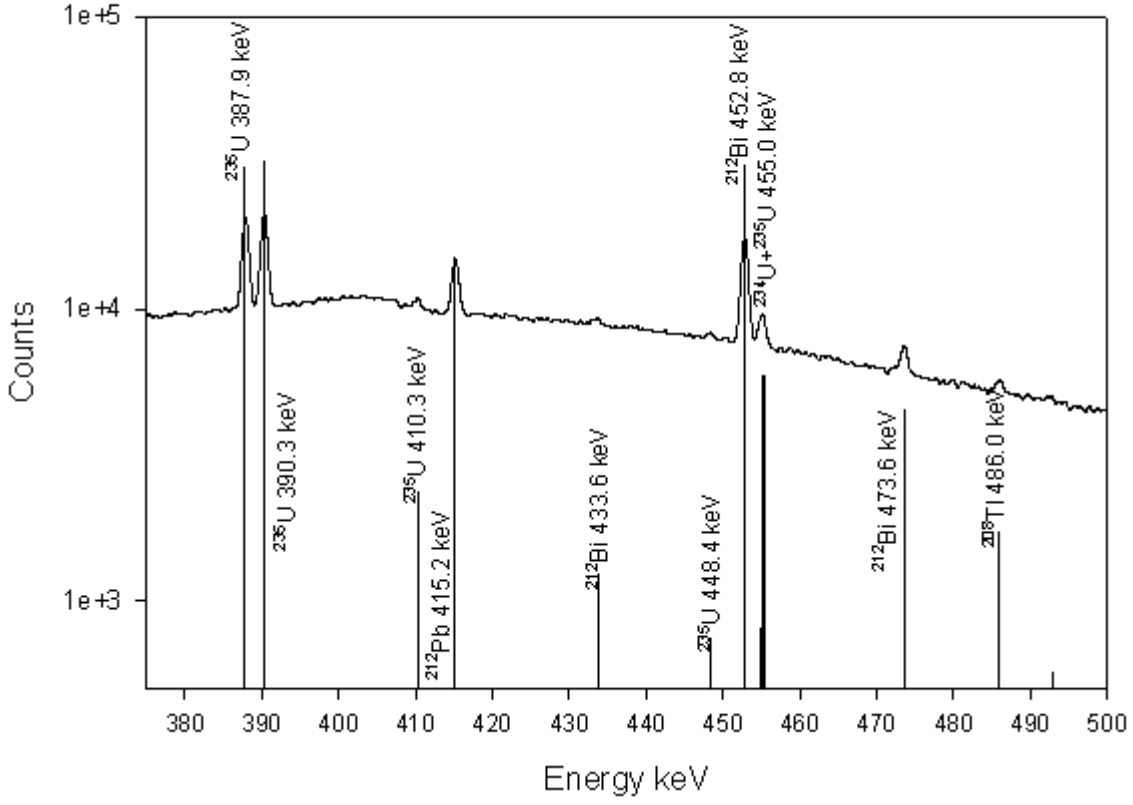
235U 345.4 keV
235U 345.9 keV
212Pb 300.1 keV
235U 301.7 keV
235U 310.7 keV
231Th 311.0 keV
235U 317.1 keV
212Bi 328.0 keV
235U 343.5 keV
235U 356.1 keV
235U 368.5 keV
235U 371.8 keV


Counts
Energy keV
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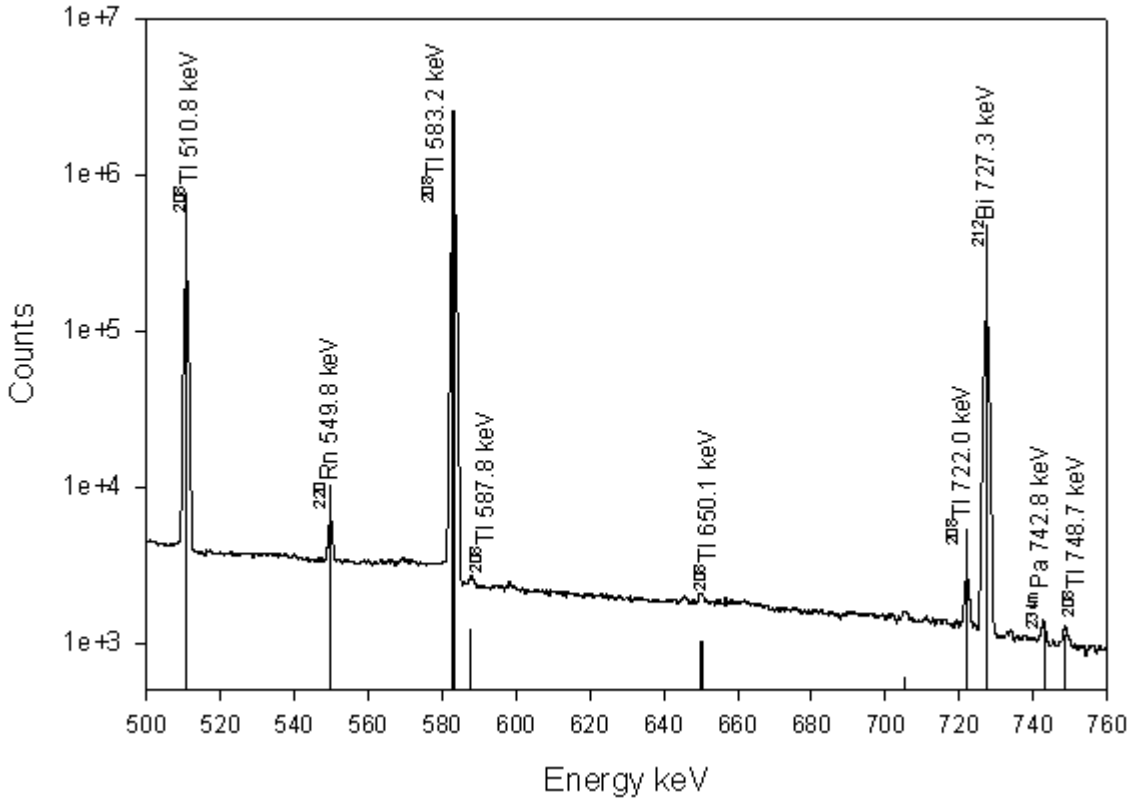
1e+4
1e+3
380 390 400 410 420 430 440 450 460 470 480 490 500
235U 387.9 keV
235U 390.3 keV
235U 410.3 keV
212Pb 415.2 keV
212Bi 433.6 keV
235U 448.4 keV
212Bi 452.8 keV
235U 455.0 keV
234U+235U
212Bi 473.6 keV
208Tl 486.0 keV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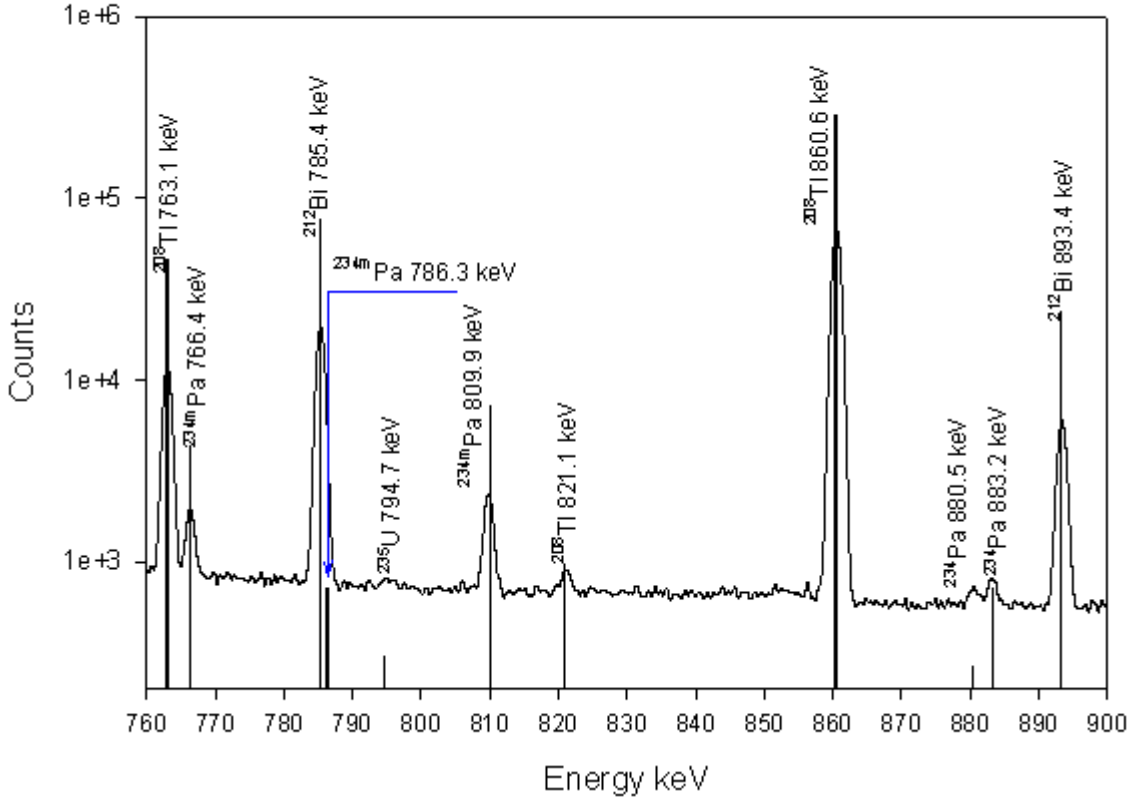
220Rn 549.8 keV
208Tl 583.2 keV
208Tl 587.8 keV
208Tl 650.1 keV
208Tl 722.0 keV
212Bi 727.3 keV
234mPa 742.8 keV
208Tl 748.7 keV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Energy keV
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234mPa 766.4 keV
212Bi 785.4 keV
234mPa 786.3 keV
235U 794.7 keV
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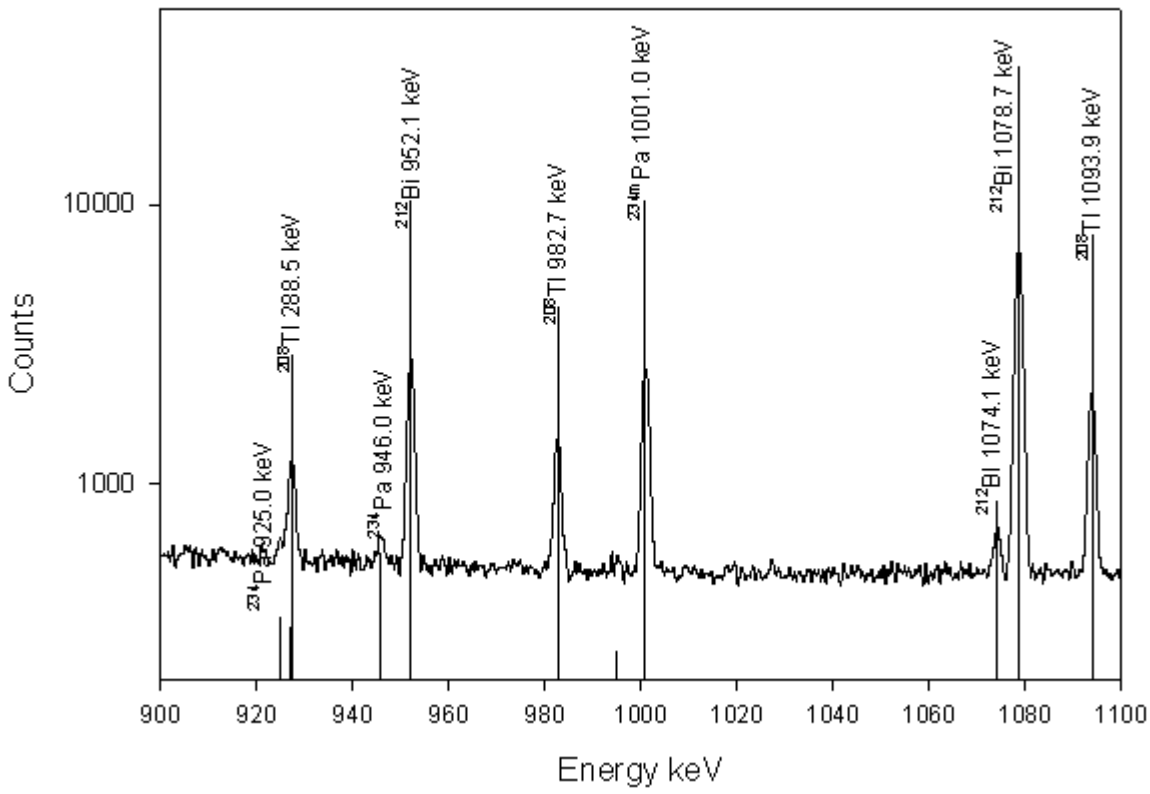
208Tl 821.1 keV
208Tl 860.6 keV
234Pa 880.5 keV
234Pa 883.2 keV
212Bi 893.4 keV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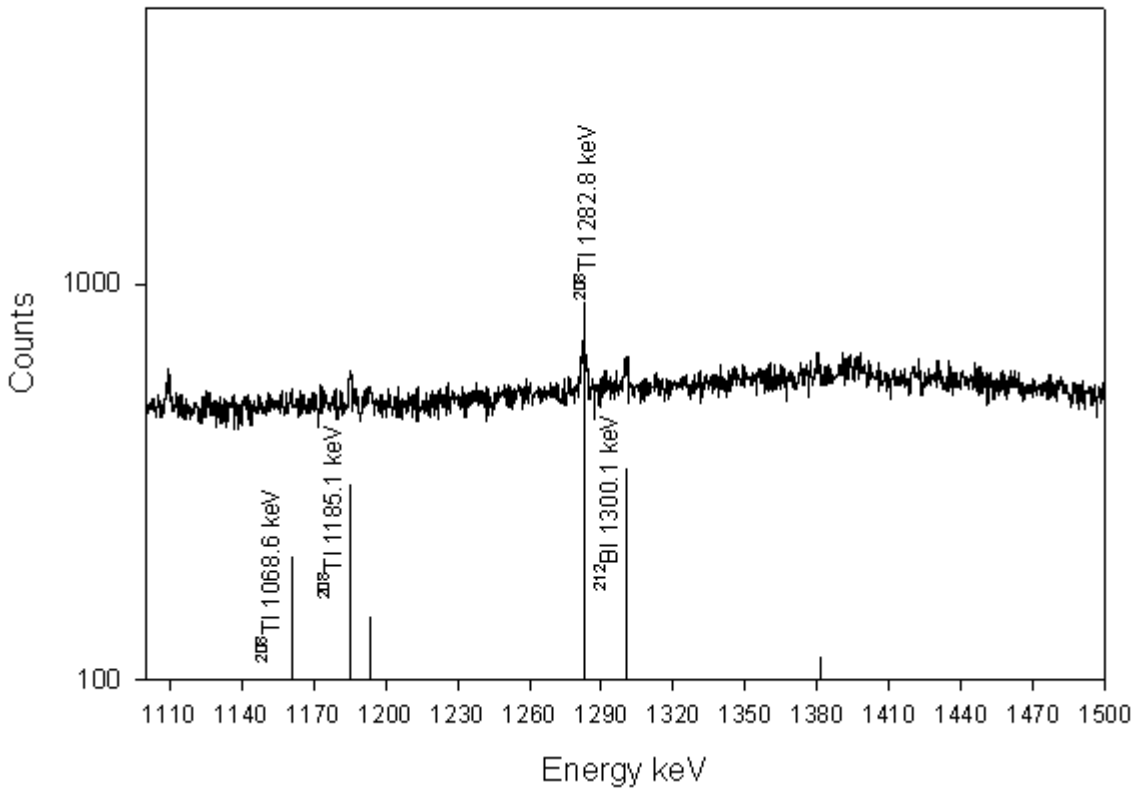
952.1 keV
982.7 keV
1001.0 keV
1074.1 keV
1078.7 keV
1093.9 keV
900
920
940
960
980
1000
1020
1040
1060
1080
1100
Energy keV


Counts
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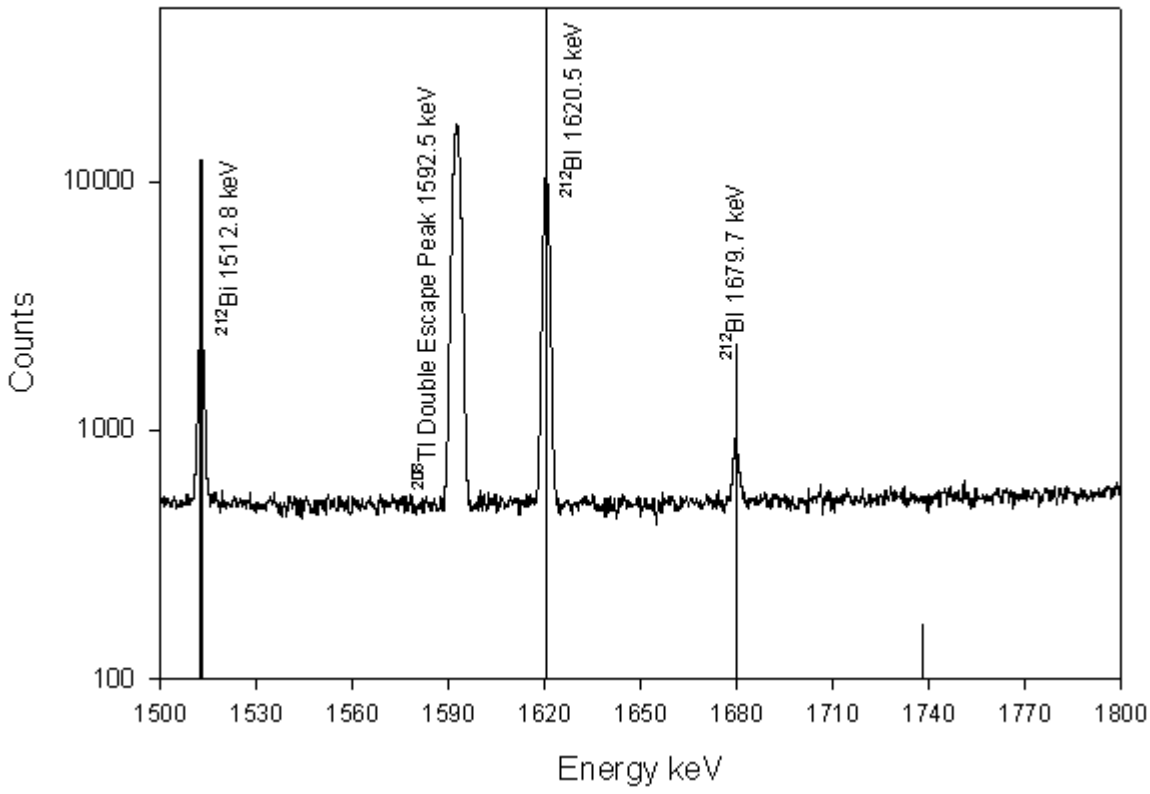
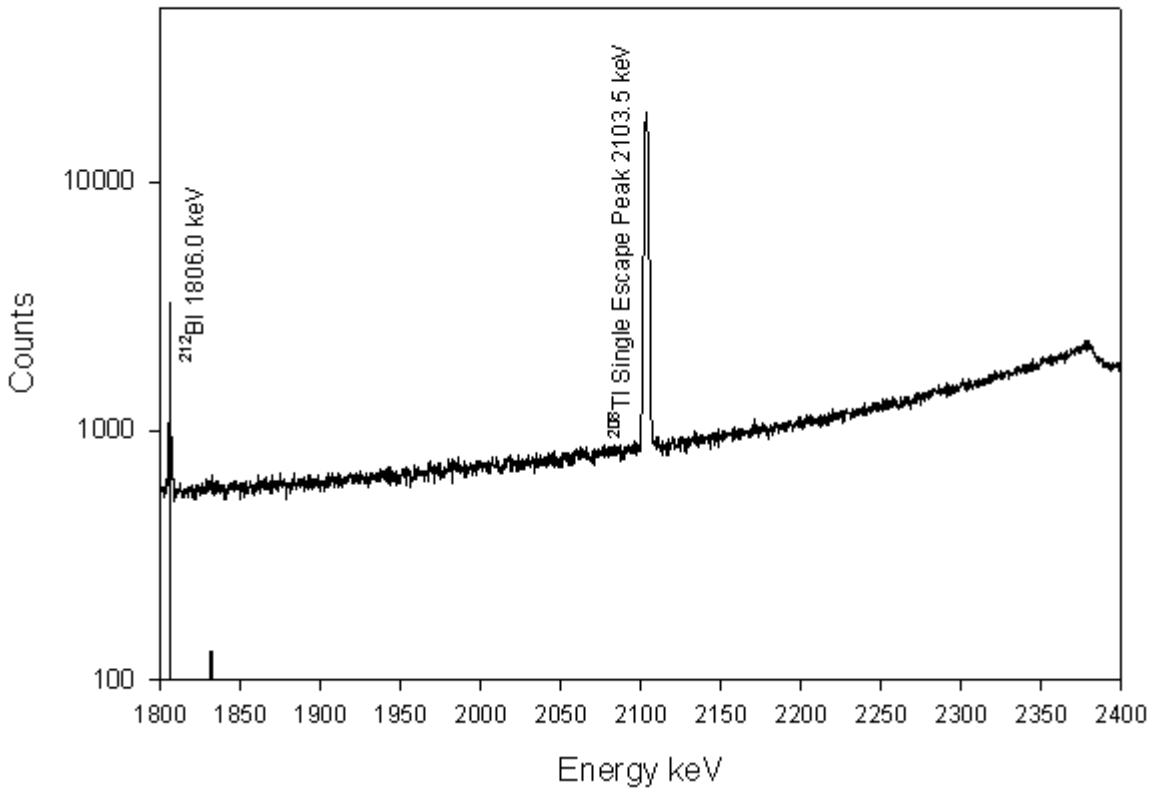
1068.6 keV
1185.1 keV
1300.1 keV
1110
1140
1170
1200
1230
1260
1290
1320
1350
1380
1410
1440
1470
1500
Energy keV


Counts
10000
1000
100
1500
1530
1560
1590
1620
1650
1680
1710
1740
1770
1800
Energy keV
212Bi 1512.8 keV
208Tl Double Escape Peak 1592.5 keV
212Bi 1620.5 keV
212Bi 1679.7 keV


Counts
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1000
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1800
1850
1900
1950
2000
2050
2100
2150
2200
2250
2300
2350
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Energy keV
212Bi 1806.0 keV
208Tl Single Escape Peak 2103.5 keV

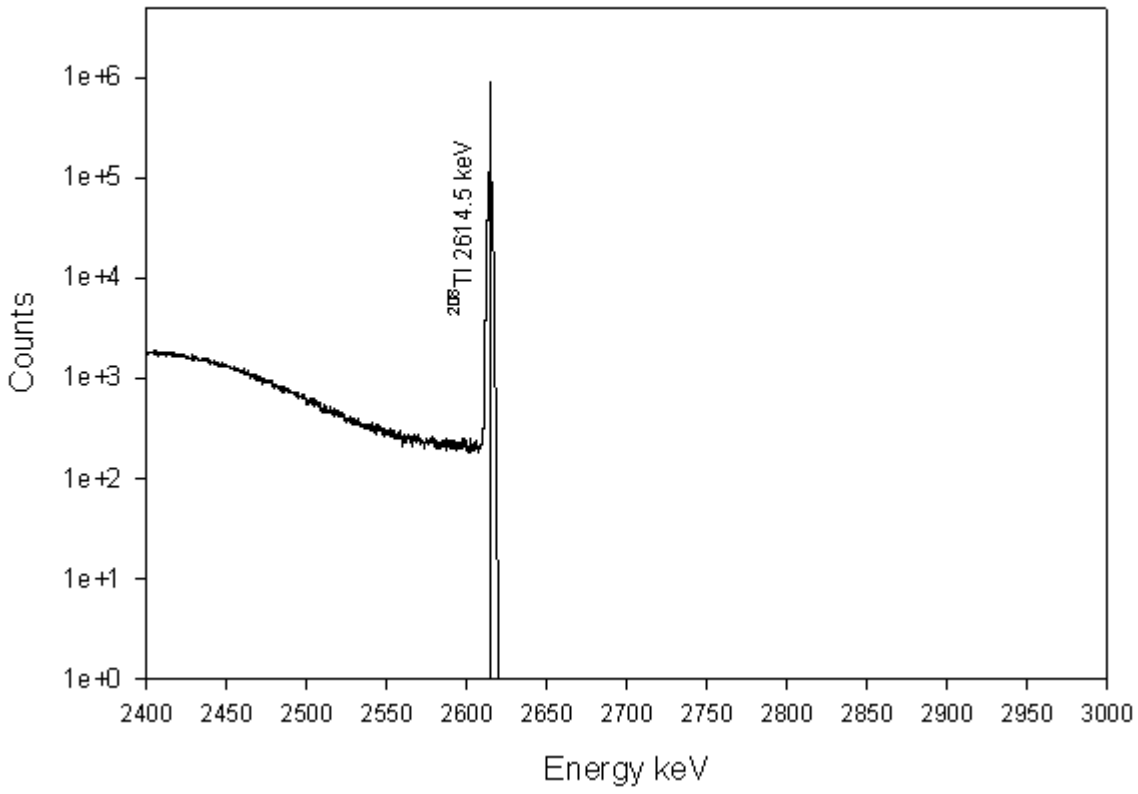

Figure A7. Assignation of constituent photoepeaks for the spectrum of Scenario 7.

APPENDIX 8 – Documents provided to participants

Information as to MALRAD Scenarios.

1. MALRAD will consist of 7 individual scenarios numbered 1 through 7. These will be distributed as individual zip files, each zip file containing all necessary information and materials as to the relevant scenario.

2. Approximately 2 weeks before the MALRAD activity starts, a practice scenario will be distributed exactly as will occur during the activity. This will allow all participants to ensure that they can open files etc.

3. Each scenario zip file will contain a .pdf file named after the scenario (ie. Scenario_X.pdf). **This file provides a description of the scenario and the material provided and should be read before analysing any material.**

4. The scenarios are intended to be "realistic"/"plausible" and have in large part been based upon actual events where possible. In some cases, isotopes/contexts have been swapped between actual events but should still be realistic.

5. The instruments featured in MALRAD are intended to be the kind that may feature in an "average" lab or such as may be brought to bear by an "average" country. Specialised laboratory instrumentation has not been included, such as low energy germanium detectors etc.

6. The aim of the activity is for the participants to provide as much information as possible – if participants feel they can suggest what the source is (as opposed to just the isotope) then they should feel free to do so.

7. The participants should be aware that the scenarios may feature activity levels many orders of magnitude higher than would normally be seen by most participants. Therefore, what may be insignificant emissions from an isotope at the levels we normally see in the lab may not be so insignificant at activities many orders of magnitude greater. Plus, it should be remembered that such activities can yield spectral features not usually encountered in the lab.

8. Some of the spectral file types may carry information as to calibration data or other similar information. Participants are encouraged to ignore this data and devise their own calibrations from such material as is provided (see below for Canberra files in particular). This will avoid any problems or artifacts that may have arisen in conversion between file types.

9. Please note that the majority of commercial analysis packages are focused towards HPGe measurements and may yield strange results when applied to the analysis of spectra from other detector types.

10. There seems to be a certain problem with Canberra .cnf files. If Genie 2000 does not find calibration information stored within the file, conducting the usual sequence of analysis can cause problems and Genie will report something like "cannot proceed without peak search results" or similar. The solution to this is to conduct an energy calibration, use it in the spectrum and save the .cnf file. Then Genie will find the information it is looking for.

11. The dose measurements where provided are not intended as absolute values of dose but should be treated in the same manner one would treat dose rates measured in the field on typical hand instruments.

12. Nuclear data used in the exercise has been taken from the online Table of Isotopes hosted by Lund University in Sweden as of June 2009. This may be found at http://nucleardata.nuclear.lu.se/nucleardata/toi/welcome.stm Participants are encouraged to check their libraries where appropriate. Participants should also consider that the libraries of a number of commercial suppliers do not contain comprehensive lists of all isotopes or comprehensive lists of energies for all isotopes.

13. Most of the scenarios only necessitate (or allow for) the identification of isotopes. Where it is theoretically possible to generate quantitative information, the situations have been engineered such that coincidence summation should not be a problem. Participants should feel free, even in the abscence of efficiency data, to report whatever they want/can.

14. In general, background has not been simulated in the spectra. Where it has, that is clearly stated.

15. For virtually all the scenarios participants can assume that an MCA lower discrimation level of 30 keV has been applied.

16. In most scenarios, daughters have also been simulated where appropriate and this should be taken into consideration during analysis.

17. The effect of neutrons or beta emissions on materials has not been simulated in any scenario. Nor do any of the scenarios feature neutron or beta detectors.

18. Please remember that scattering can be an issue in spectra recorded for sources with heavy shielding and certain detectors.

19. Thorough information on the detectors has not been supplied during the exercise stage as it was felt that such information may not be available in early reponse situations nor would it be likely that the type of analyses necessitating such information would be practicable during early responses.

20. Please note that the scenarios are not country "specific". Do not eliminate an isotope as a candidate based on the supposition that "*country X doesn't have these sources*" or whatever.

21. Although some of the situations in MALRAD appear difficult, the situations presented are those which the participants in MALRAD could reasonably be expected to handle. In cases where participants feel a scenario is outside their area of expertise, they should indicate which scenarios they choose NOT to report for.

22. Participants can report their results using a simple Word or text file. Just write the number of the scenario and what the source is as well as any other information one may wish to report.

23. The files are named according to the following convention:

    Scenario_X_YYYYY.*.* where X indicates the scenario number and YYYYY is either "point" or "source" indicating whether the spectrum is of the actual source or a check point source as described in the material accompanying each scenario.

24. The spectra are provided in a range of formats. These include:

Standard ORTEC/ADCAM .chn files

Standard ORTEC .spc files

Standard IEC ASCII .iec files

Standard IEEE ASCII .asc files

SAMPO 90 readable .sam files

Old SYSTEM 100 format .mca files (should be readable by Genie 2000 as well)

Text file (.txt), one column, first row: channels live time realtime start energy keV/channel, second and third rows are time information

Text file (.txt), two column (indicated by designation "b" in the file name), same as above but with channel as own column

Standard CANBERRA .cnf files

Accuspec .dat file

IAEA .spe file

Excel .csv file (channel, count no time information included).

Context Material Provided to Participants for each Scenario.

Scenario 1.

Police receive warning of a bomb placed in a city centre location and due to previous intelligence regarding attempts by the relevant grouping to obtain radioactive materials, request assistance with respect to a suspicious vehicle found near an embassy. A collimated standard 3x3 inch NaI detector was mounted on a remotely controlled vehicle and positioned at the side of the suspect vehicle which had not been opened. The vehicle, a small lorry, was two meters wide and the detector was placed at and up against the side of the cargo compartment (the distance between the detector and the side of the truck is 0 cm). A spectrum was accrued over a period of ten minutes. Two dose measurements were made, one at the same position at which the spectrum was taken and the second at a point one meter further back along the same axis. The background dose in the area was 0.11 μSv/hr. The dose rate at position one (side of the truck) was 0.5 μSv/hr and at position 2 (1 m away from the side of the truck) was 0.21 μSv/hr. A spectrum for a point source of ^{241}Am, ^{109}Cd, ^{137}Cs, ^{60}Co and ^{88}Y had earlier been taken at a distance of 10 cm from the detector face and is provided.

Note: a background spectral contribution has been added.

Materials provided:

Two spectra, in a number of formats are provided.

Scenario_1_source(range of formats) - the spectrum accrued from the side of the truck.

Scenario_1_point.(range of formats) - spectrum of the point source taken earlier.

Scenario 2.

Customs officials stop a car at a border crossing driven by a man known to be involved in international smuggling and criminal activities. A search of the car is made and a steel cylinder is found hidden in the car. The accompanying materials suggest that the cylinder may contain radioactive materials and the cylinder is taken away for analysis. The cylinder is some 4 cm in diameter and 5 cm in height and is welded shut such that it cannot be opened. It was measured on a standard HPGe detector of some 50% relative efficiency with

resolution of 1.9 keV at 1332 keV by being suspended centrally some 15 cm above the detector face and measured.

A point source of ^{241}Am, ^{109}Cd, ^{137}Cs, ^{60}Co and ^{88}Y had earlier been taken at a distance of 10 cm from the detector face.

Materials provided:
Two spectra, in a number of formats are provided.
Scenario_2_source.(range of formats) - the spectrum obtained from the cylinder.
Scenario_2_point.(range of formats) - spectrum of the point source taken earlier.

Scenario 3.

A scientist from a large medical research facility is admitted to hospital suffering from what appears to be radiation sickness. The relevant authorities are alerted and upon discovery that the scientist does not work with radioactive materials, a search is initiated of the facility, its grounds and his home by search teams equipped with dose meters and a range of detectors. One team registers anomalous dose readings in the vicinity of what turns out to be the scientist's car and a spectrum is taken using a small CdZnTe (3 cc) detector from the hospitals medical physics department. A point source of ^{241}Am, ^{137}Cs and ^{60}Co was measured to establish the energy calibration. A dose meter was also used to establish the direction of maximum dose and two measurements were taken: the first of these was 1.8 m from the side of the car where the dose was 229 μSv/hr and one 2 m further back where the dose was 57 μSv/hr.

Materials provided:

Two spectra, in a number of formats are provided.
Scenario_3_source.(range of formats) - the spectrum obtained from outside the car with the CdZnTe detector.
Scenario_3_point.(range of formats) - spectrum of the point source taken earlier.

Scenario 4.

A newspaper receives a warning from a known extremist environmental group that public rooms of some government buildings have been contaminated with radioactive

materials in a radical act of protest at an upcoming governmental vote on nuclear power. The warning is viewed as credible by the authorities in light of reports of suspicious activities at a number of nuclear facilities in a neighbouring country in the preceding months. The relevant authorities are dispatched to search for contamination and cleaners report having observed a black powder in the carpet of one of the public seminar rooms. A 3 x 3 inch NaI detector is employed to make measurements and this was mounted vertically some 50 cm above the surface of the carpet in question. A point source of ^{241}Am, ^{109}Cd, ^{137}Cs, ^{88}Y and ^{60}Co was measured to establish the energy calibration. The measured background corrected dose rate was of the order of 20 to 25 μSv/hr above the carpet.

Materials provided:
Two spectra, in a number of formats are provided.
Scenario_4_source.(range of formats) - the spectrum obtained from above the carpet.
Scenario_4_point.(range of formats) - spectrum of the point source taken earlier.

Scenario 5.

Passengers on a city centre bus report a suspicious dripping package under a seat and report it to the driver who upon closer inspection notices what appears to be plastic pieces and some kind of white powder in a plastic bag. One of the pieces seems to have a trefoil symbol on it and as a result of this, the driver notifies the police who subsequently notify the relevant authorities that a radioactive source may be present on the bus. The authorities arrive and a short spectrum was taken using a 2 x 2 portable NaI detector at a distance of 1 m from the source. A dose rate measurement was made at 1 m distance and this was 131 μSv/hr. A point source spectrum of ^{241}Am, ^{109}Cd, ^{137}Cs, ^{88}Y and ^{60}Co was taken at a distance of 10 cm from the detector face.

Note: a background contribution has been added.

Materials provided:
Two spectra, in a number of formats are provided.
Scenario_5_source.(range of formats) - the spectrum from the source on the bus.
Scenario_5_point.(range of formats) - spectrum of the point source taken earlier.

Scenario 6.

Two people are found dead and autopsy reveals that the most probable cause of death was exposure to a radioactive source of considerable strength. Searches of the homes of both by the authorities reveal nothing until elevated readings are located in the yard of one of the homes. The radiation appears to emanate from a pile of junk metal but dose rates are such that the pile cannot be disturbed without investigation. A spectrum was taken at a distance of approximately 5 m from the pile surface using a small CdZnTe detector. Two dose measurements were made: one at the same point as the spectrum was taken which was 0.802 mSv/hr and one 5 m back which was 0.201 mSv/hr both having been corrected for background. A point source of ^{241}Am, ^{109}Cd, ^{137}Cs and ^{60}Co was measured earlier to check the detector.

Note: background spectrum not added.

Materials provided:

Two spectra, in a number of formats are provided.

Scenario_6_source.(range of formats) - the spectrum obtained 5m from the pile.

Scenario_6_point.(range of formats) - spectrum of the point source taken earlier.

Scenario 7.

During a police raid on a suspected radical group, a number of materials are seized and declarations by suspects and the context of the find indicate the potential for some of the materials being radioactive. A 10 g aliquot of a fine brown powder is presented to the relevant authorities for analysis with the request that as much information as possible be obtained as to the material. The unknown material was counted on a standard coaxial HPGe detector in a plastic cylindrical geometry at a distance of 10 cm. The apparent density of the material was 10.95 +/- 0.1. In order to calibrate the detector, an aqueous solution of the following nuclides was presented to the detector in the same geometry and at the same distance as was to be used for the unknown. ^{241}Am – 30000 Bq, ^{57}Co – 10000 Bq, ^{60}Co – 10000 Bq, ^{54}Mn – 10000 Bq, ^{65}Zn – 10000, ^{88}Y – 10000 Bq, ^{137}Cs – 10000 Bq and ^{109}Cd – 10000 Bq and counted in the same configuration (ie. 10 cm above the detector).

Note: background has not been simulated. Activities of the calibration solution are those at the time of counting of the spectrum.

Materials provided:

Two spectra in a number of formats are provided

Scenario_7_calibration.(range of formats) - the spectrum from the calibration solution

Scenario_7_source.(range of formats) – the spectrum from the unknown material.

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Abstract

The MALRAD activity was intended to provide an exercise activity with respect to gamma ray spectrometric response to malevolent situations involving radioactive sources. Such situations can often be characterised by high activity sources in difficult contexts where the response is by necessity conducted with less than optimal instrumentation. Seven scenarios were developed based on previous incidents where possible and gamma spectral data and other information was disseminated to participants who were given one week to respond to each scenario with as much information as possible. In total 14 individual laboratories responded. The majority of laboratories were in a position to satisfactorily identify sources where single sources were used in situations with no complicating factors. For those scenarios involving heavy shielding som difficulties were encountered due to distortion of the spectrum from that which would normally be viewed as characteristic for the isotope in question. Special nuclear materials such as reprocessed enriched uranium and weapons grade plutonium provided different challenges and there were indications in the reponses from participants of unfamiliarity with these materials.

Key words Gamma ray spectrometry, special nuclear materials, sources,