# IDENTIFICATION AND CALCULATION OF ACTIVITY OF UNKNOWN ISOTOPE FROM SPECTRAL ANALYSIS IN A RADIOLOGICAL DISPERSION DEVICE (RDD) INCIDENT

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# IDENTIFICATION AND CALCULATION OF ACTIVITY OF UNKNOWN ISOTOPE FROM SPECTRAL ANALYSIS IN A RADIOLOGICAL DISPERSION DEVICE (RDD) INCIDENT

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# Summary

In an event of a radiological dispersion device (RDD) detonated by terrorists in a high population density area like Atlanta, the hospitals and other medical facilities will be overwhelmed by people who may or may not have been contaminated by radioactivity. Under such chaotic circumstances, it would be desirable to identify people who have inhaled radioactive particles and direct them immediately for further treatment. Prompt identification of radioactive material would accelerate local authorities' response time for protective action.

A portable 3" by 3" NaI detector, which is cheap and widely available at most universities, was studied as a tool to identify and calculate the activity of unknown radioisotopes for such an RDD event. The isotope identification method employed was regression analysis using measured responses for radioisotopes behind Lucite slabs simulating various chest wall thicknesses. An algorithm was developed to identify and calculate the total activity of the isotopes regardless of chest wall thickness.

The algorithm was successful in identifying the unknown isotope. It provided correct location of isotope in almost all cases while determining the activity of unknown isotope within 4 to 35 % of error of the known value.

# Chapter 1

# Introduction

A radiological dispersion device (RDD) or a dirty bomb is a combination of an explosive and radioactive material. It is not a nuclear weapon and it will not cause massive destruction, but this device could release radionuclides into the environment. It is cited as the most likely device that the terrorists would use (NRC fact sheet).

The impact of a dirty bomb depends on a number of factors like size of the explosion as well as the amount and type of radioactive material and weather conditions (NRC fact sheet). Hospitals, industries and academic institutions for medical, research and industrial applications extensively use radioactive materials worldwide. Once the isotopes are utilized, they are known as disused sources (Fergusson 2003). Disused sources ideally are sent to disposal facilities operated by source manufacturers or the government. Lack of a proper disposal facility or high disposal cost may deter users from properly disposing of disused sources. This may result in theft or diversion of sources. Such unused sources are called orphan sources. Radioactive sources that do not go through the standard life cycle of usage and disposal have a greater risk of diversion for terroristic purposes. Orphan sources do not come under the regulatory controls, as they have been stolen, lost or abandoned. About 500,000 of 2 million sources in the U.S are susceptible to becoming orphan sources. (Fergusson 2003)

Although, orphan sources exist in almost all countries, the greatest risk is from former Soviet Union where, thousands of high-risk orphan sources are available through out the region. It is assumed that the terrorists would try to obtain orphan sources from these regions. (Sohier. 2006)

The selection of radioactive sources by terrorist would depend on radiotoxicity, availability and half-life. For example cesium chloride with high concentration of Cesium-137 in powder form, can be dispersed in the atmosphere by such an explosion. Based on these criteria, eight radioisotopes have been identified which the terrorists can use in a RDD. These are Americium-241, Californium-252, Cesium-137, Cobalt-60, Iridium-192, Plutonium-238 and Strontium-90 ($^{241}Am$, $^{252}Cf$, $^{137}Cs$, $^{60}Co$, $^{192}Ir$, $^{238}Pu$ and $^{90}Sr$ respectively (Fergusson 2003)). The data for these isotopes are given in Table 1(www.ead.anl.gov)

Table 1: Isotope Data

| Isotope | Half Life | Specific Activity (Ci/g) | Decay Mode | Radiation Energy(MeV) | | |
|---|---|---|---|---|---|---|
| | | | | Alpha (α) | Beta (β) | Gamma (γ) |
| Am 241 | 430 yr | 3.5 | α | 5.5 | 0.052 | 0.059 |
| Cs-137 | 30 yr | 88 | β | - | 0.19 | 0.662 |
| Co-60 | 5.3 yr | 1,100 | β | - | 0.097 | 1.17,1.33 |
| Pu-238 | 88 yr | 17 | α | 5.5 | 0.011 | 0.0018 |
| Ir-192 | 74 days | 9,200 | β,EC | - | 0.22 | 0.82 |
| Sr-90 | 29 yr | 140 | β | - | 0.20 | Y-90 |
| Na-22 | 2.6 yr | 6243 | β + | - | 0.546 | 1.275 |

The uses of these sources are shown in Figure 1. It is clear from this chart that these isotopes have many commercial uses and hence are widely used in the industry. As these sources are highly destructive it is crucial to store them in highly secured areas and have appropriate disposal arrangements for these sources. This is not always the case as disposal/handling. Failure to dispose of such sources increases the risk of theft.

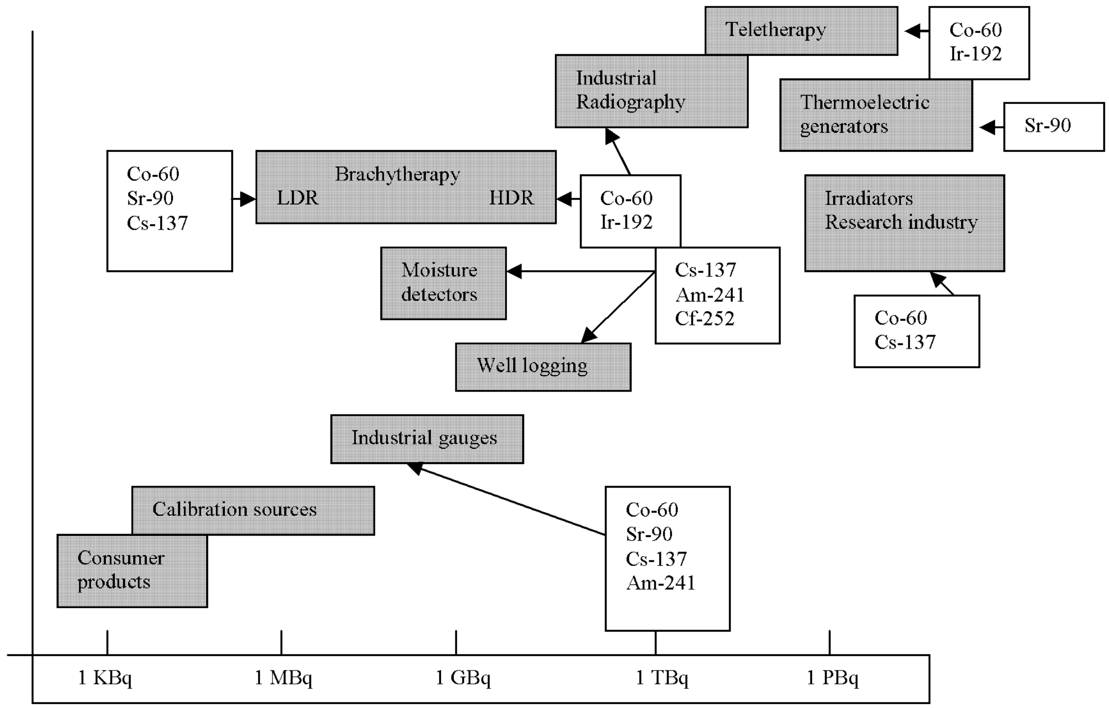


Figure 1: Commercial Radioactive Sources (IAEA-2001)

The purpose of this thesis is to test whether a 3" by 3" NaI detector connected to a multichannel analyzer (MCA) can be used to identify and calculate the activity of unknown isotope following a radiological incident. As governments control the use and sale of Pu-238, it would be very difficult for a terrorist to procure Pu-238 from the black market without arousing suspicion. The rest of the sources can be obtained with effort and money. The isotopes utilized for his experiment were Cobalt-60, Cesium-137, and Sodium-22. Although, Sodium-22 is not from the list (Fergusson 2003), it was selected to test the algorithm. A portable 3" by 3" NaI detector, was used to identify and calculate the activity of unknown radioisotope using regression analysis. An algorithm was developed to recognize and calculate activities of unknown isotopes for different chest wall thicknesses.

# Chapter 2

## Measurements of the Responses

The instrument used was a 3" by 3" NaI detector Model 905-3 manufactured by the ORTEC[1]. The high atomic number of iodine in NaI (Tl) crystals yields a high efficiency for Cs-137 gamma-ray detection. Resolution for a 3-inch diameter by 3-inch length crystal is about 7%. The details of a typical NaI detector are shown in Fig 2

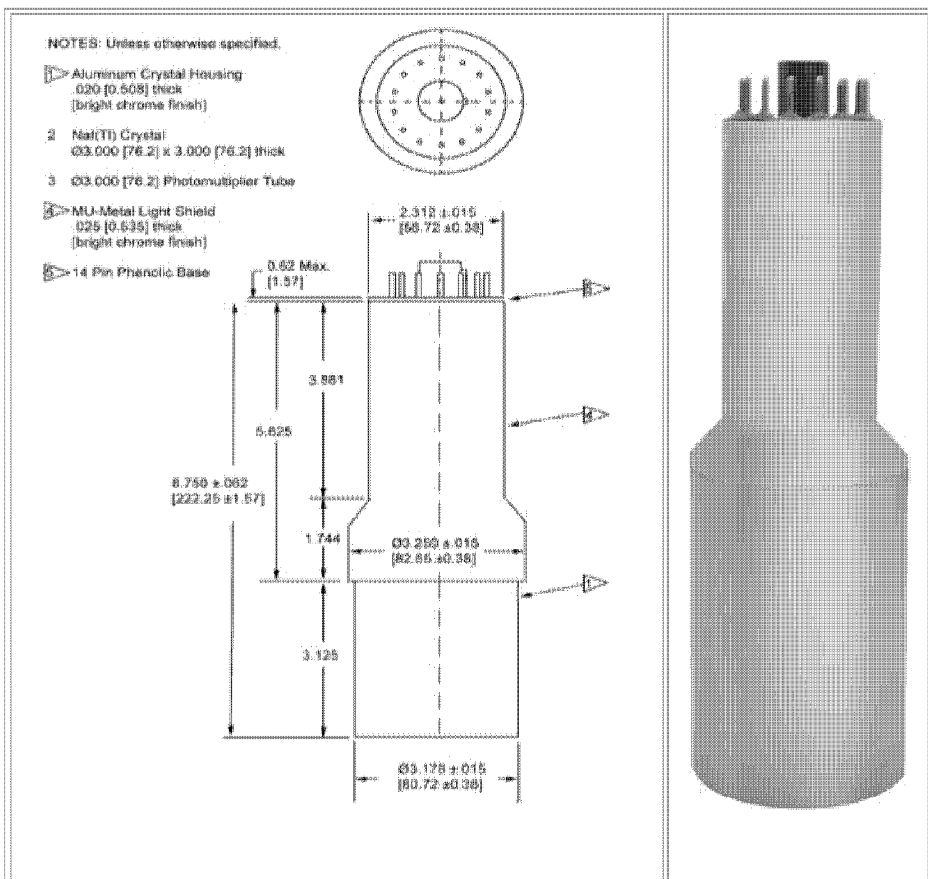


Figure 2. NaI detector

[1] ORTEC, www.ortec.com

Three isotopes $^{60}Co$, $^{37}Cs$ and $^{22}Na$ of various activities were used in the experiment. The details of the isotopes are given in Table 2.

Table 2: Sources Used in the Study

| Element | Half life $T_{1/2}$ | Assay date | Initial Activity | Activity at the time of experiment |
|---|---|---|---|---|
| Co 60 | 5.28 years | 12-14-05 | 1 µci | 0.9 µci |
| Co 60 | 5.28 years | 05-01-01 | 8.9 µci | 4.7 µci |
| Cs 37 | 30.7 years | 12-14-05 | 1 µci | 1 µci |
| Cs 37 | 30.7 years | 05-01/01 | 10.1 µci | 9.1 µci |
| Na 22 | 2.6 years | 05-01-01 | 9.2 µci | 1.8 µci |

The following is a picture of the slab phantom used for this experiment. The slab consists of lucite slices in increments of 3mm, 6mm, 12mm, 18mm and 24 mm respectively. It was used to simulate the transport of photons inside a human chest. The isotopes were placed behind the slab phantom for different thicknesses and readings were taken using the NaI detector.

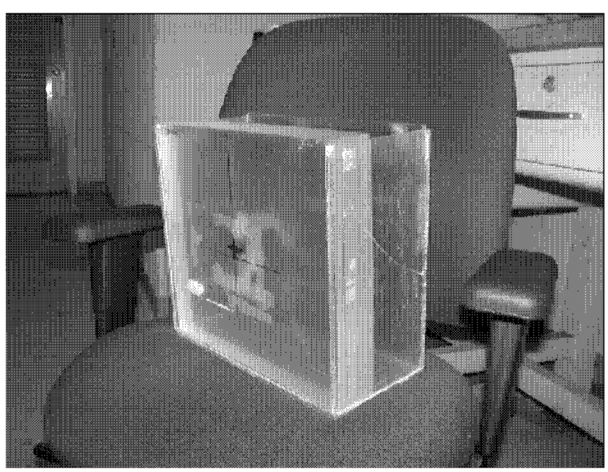

Figure 3. Slab phantom to simulate chest thickness

These spectral measurements were made using an unshielded NaI scintillator connected to the multi channel analyzer. The detector was placed in contact with the face of the slab and point sources were placed behind the slab. Dead time was kept under 15 %. If the sources were hot, resulting in higher dead time then the distance between the sources and detector was increased till the dead time was brought down to 15 %.The analysis was carried out using the isotopes given in Table 2. The following are pictures of the experimental set-up.

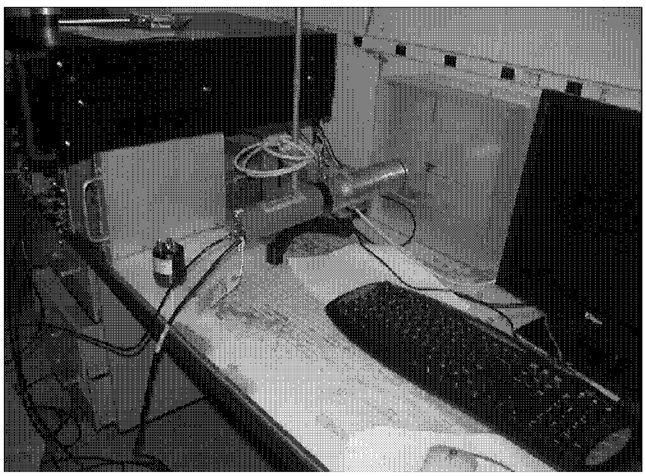

Figure 4. Experimental set-up.

Figure 5. Alternate view of Experimental set-up.

The spectrum analysis was performed using the Maestro software from ORTEC. Maestro records the spectrum in count per unit activity to channels .The pulse height spectrum was binned into 1024 channels. In the present work, each channel corresponds to 1.625 keV energy width.

Spectral measurement of each isotope was performed for 6mm, 60mm, 90mm, 105mm, 135mm and 150mm thicknesses of lucite between the source and the detector. The objective was to mimic the different thicknesses of human chest. A spectra was accumulated for 10 minutes attenuation of the photons through spectrum wall(live time) for each thickness and the experiment was run for all the isotopes listed in Table 2. The reason for counting 10 minutes instead of longer time was due to the short time which the emergency response teams will have during an actual RDD incident. However, to make a response matrix, one should use a very long count time.

The detector background was accumulated for run for 20 minutes and normalized for 10 minutes. The net count rate was then calculated by subtracting the counts from the normalized background.

To obtain better results it was important to restrict the dead time to less than 15%. This was achieved by adjusting the distance between the detector and the phantom. For example, an isotope with a lower activity can be accurately detected by placing the detector almost in contact with the phantom, while for higher values of activity the detector-phantom distance should be increased accordingly. The following picture shows the detector reading an isotope of lower activity. The same set-up with a larger distance can be used to read higher activity isotope.

Figure 6. NaI detector reading a weak isotope.

There were total of seven spectra for each of the three isotopes and total of (7x3) 21 at different depths of Lucite. The spectra for each isotope are plotted as shown in Figure 7 through Figure 15. A decrease in the height of the photon peaks be observed as the thickness of the Lucite increases due to the attenuation of the photons. The lower pulse height counts increase with lucite thickness due to photons scattered in the slab.

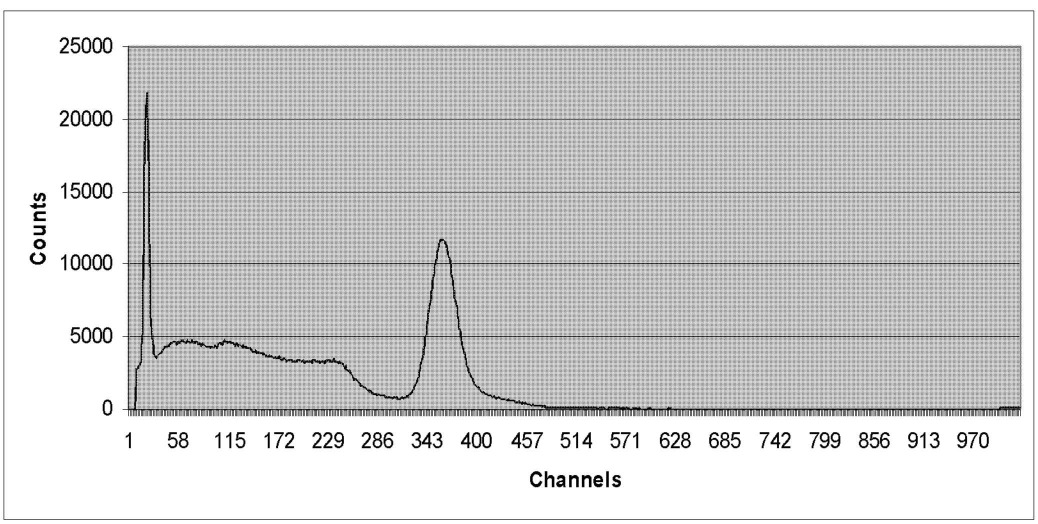


Figure 7. Cs-137 with 1 μCi activity tested with 6mm Lucite Thickness.

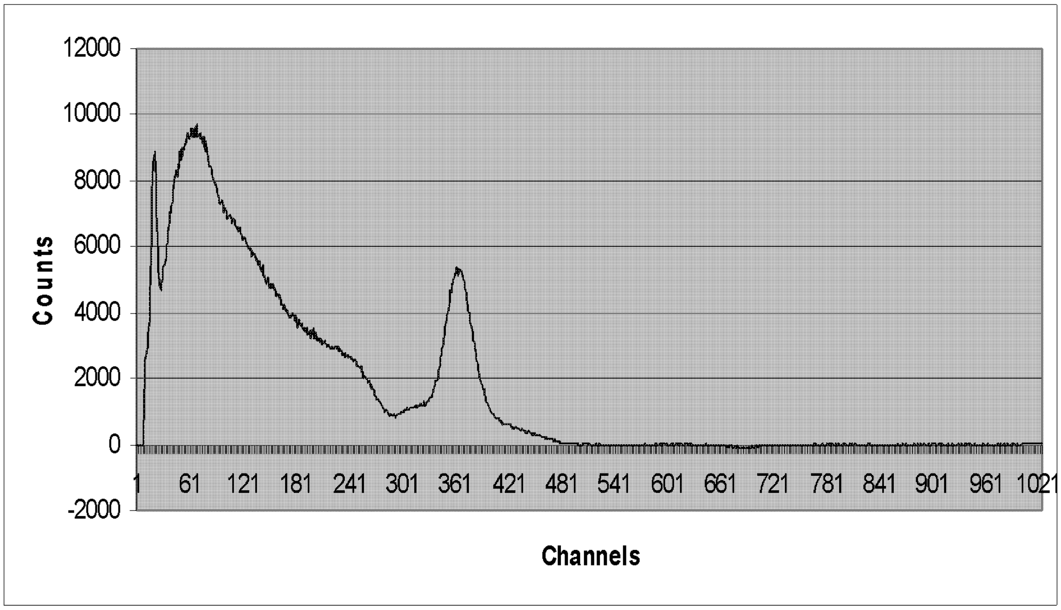


Figure 8. Cs-137 with 9.1 μCi activity tested at 90mmv Lucite Thickness.

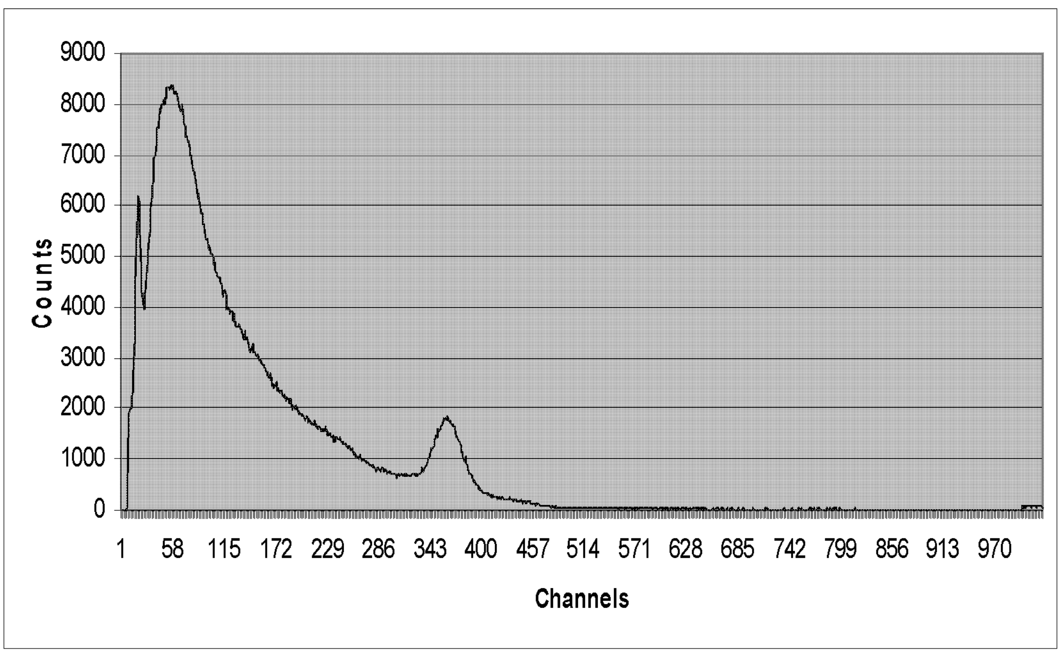


Figure 9. Cs-137 with 9.1 μCi tested at 150mm Lucite thickness.

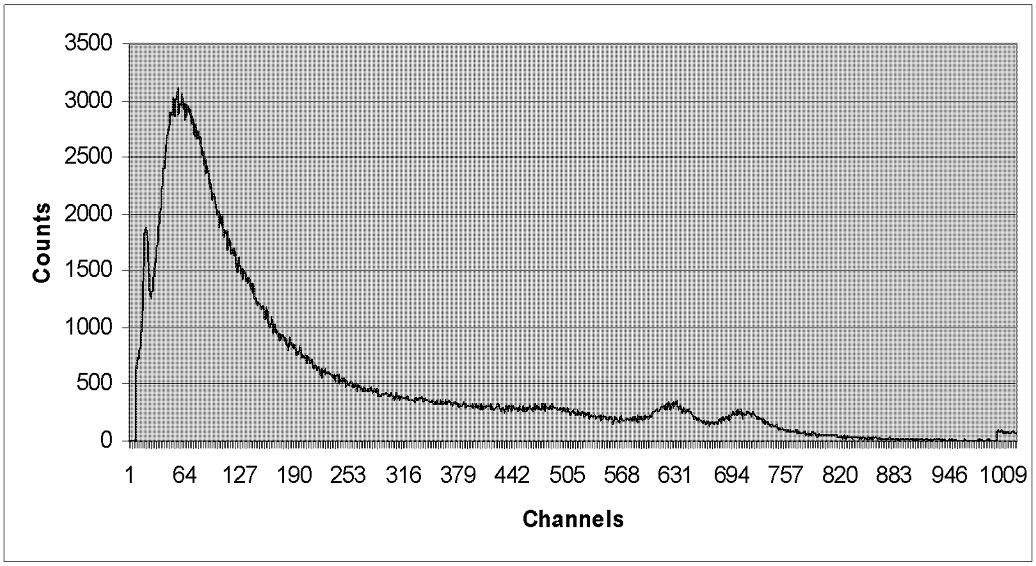


Figure 10. Co- 60 with 1 μCi activity tested at 6mm Lucite Thickness.

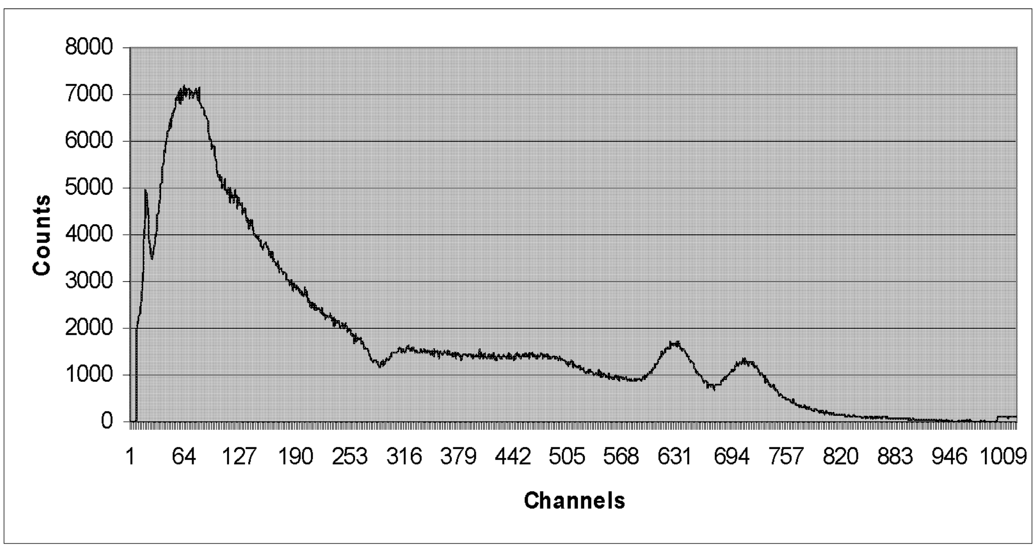


Figure 11. Co-60 with 4.73 μCi activity tested at 90 mm Lucite Thickness.

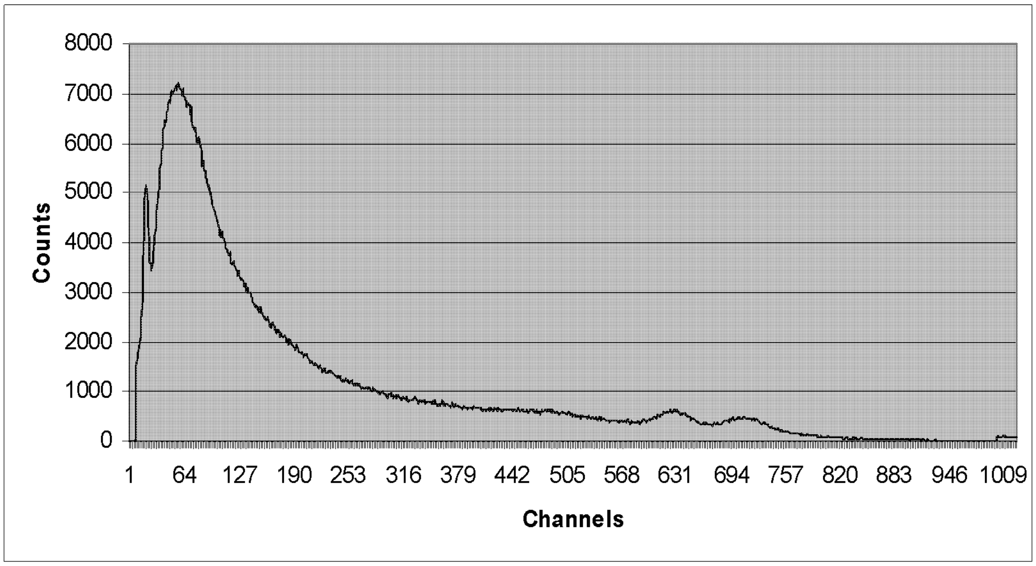


Figure 12. Co-60 with 4.73 μCi tested at 150 mm Lucite Thickness.

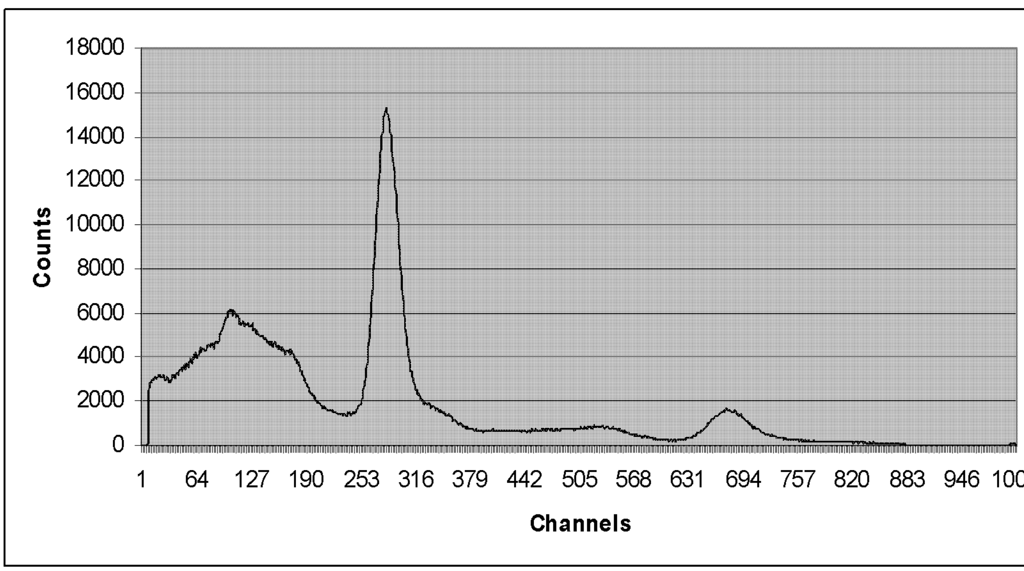


Figure 13.Na-22 with 1.85 μCi tested at 6 mm Lucite Thickness.

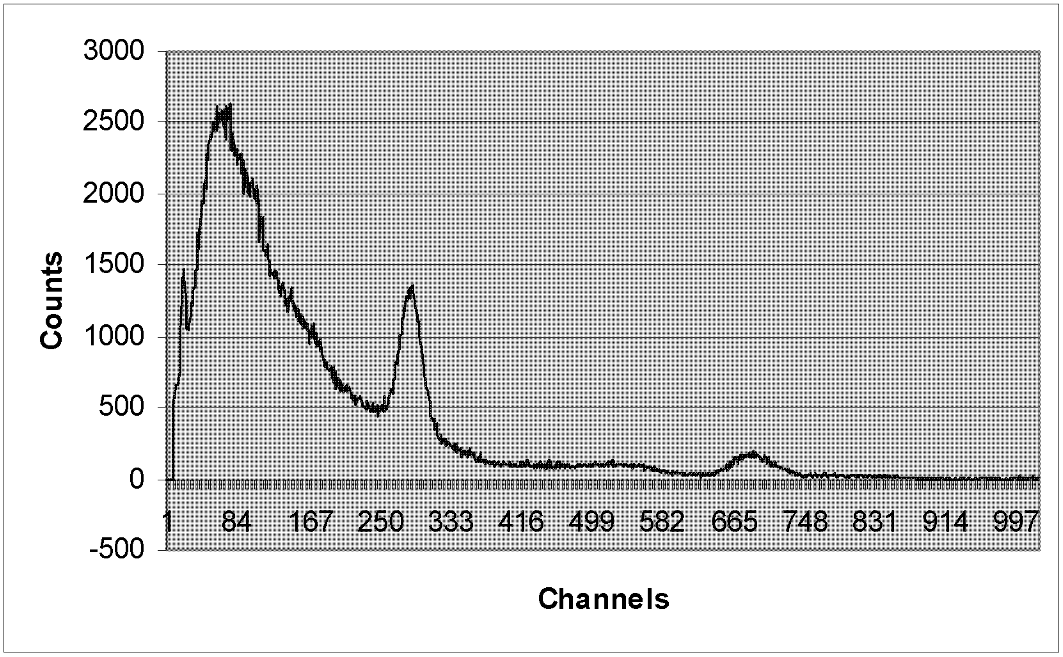


Figure 14. Na -22 with 1.85 μCi tested at 90mm Lucite Thickness.

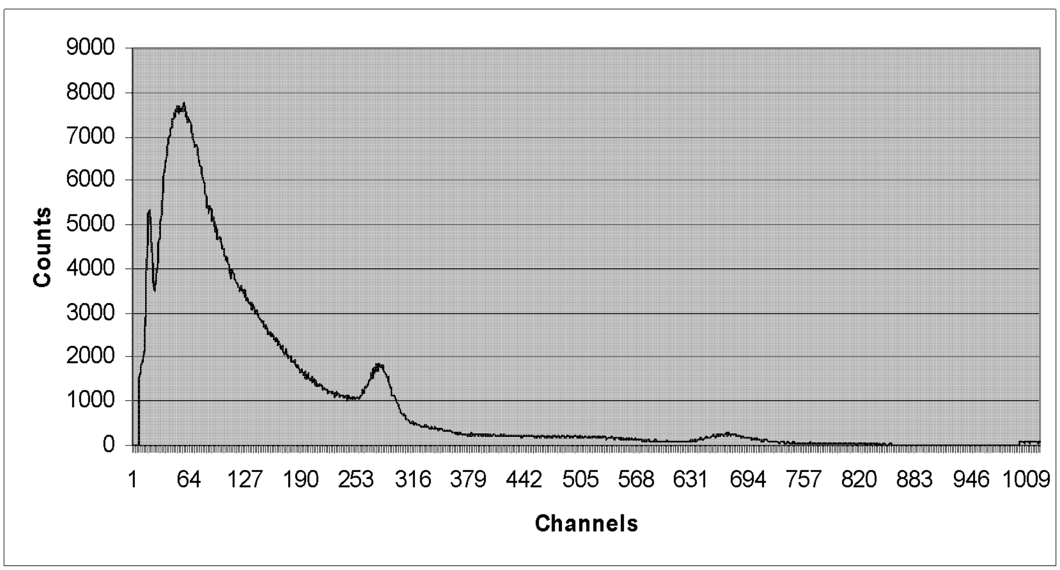


Figure 15. Na – 22 with 1.85 μCi tested at 150 mm Lucite Thickness.

# Chapter 3

## Algorithm Development

The measured responses represented 21 spectra, each in turn represented by a 1024 by 1 vector. Initially, the data were reduced by compressing the number of channels from 1024 to 25. The counts for the new channels were calculated by summing over 40 channels of the measured spectra. Data only from channels 25-1024 were used in order create the data in the new 25 channels dataset. Data from below channels 25 were not considered to contain useful information. None of the isotopes in the spectrum library had significant features above channel 903 so the data above 903 channels were not used.

This method of sorting raw data did not produce desired results as the compression of channels resulted in loss of resolution of the photopeaks, which created overlap between the data of different isotopes and the program failed to make correct identifications. The following graph shows the distorted peaks with 25 integrated channels.

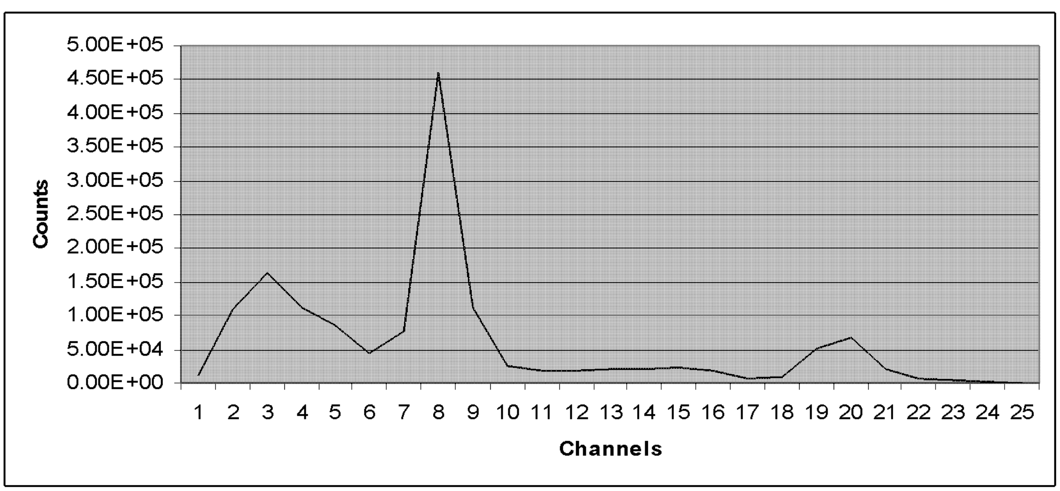


Figure 16. Distorted Sodium spectrum with 25 channels.

Instead, a longer vector of 700 bins was created for each isotope. Although, this approach required more data handling by the algorithms, the better representation of the photopeaks enabled the algorithm to perform better. A library of the 700 channels spectra for each isotope was created and a MATLAB algorithm was written using an unconstrained least-squares method. According to the algorithm, these library data are convolved with the unknown isotope activity at each depth to make the isotope identification.

Once the isotope is identified, the program passes the data set to another algorithm for determination of activity at various depths in the chest. A library for each of the three isotopes was created from the spectra measured behind 6mm, 90mm and 150mm of Lucite. The spectra were not measured at 0 mm on the assumption that person would be externally washed with water before testing. Hence, there would be no contamination at 0 mm of chest thickness. The reason for not using the other thickness was that gamma rays are highly penetrating and there is little attenuation in small increments of 10- 15 mm Lucite thickness.

In radiation measurement, folding and unfolding operations are applied to the experiment data. The shape of the measurement when the source, its depth and detector response is known is given by the Fredholm integral equation (Tsoulfanidis):

$$M(E) = A\int_{0}^{\infty} R(E,E^{'})O(E^{'})$$

Where

M(E)dE = measured spectrum – no. of particles recorded as having energy between E and E+dE.

A×O(E′)dE′ = source spectrum = no. of particles emitted by the source with energy between E and E+dE.

R(E,E′)dE = response function or energy resolution function of the detector = probability that a particle emitted by the source with energy E′ will be recorded with energy between E and E+dE.

Although, pulse height distribution is measured but the energy calibration of the system gives a one –to- one correspondence between recoil electron energy and pulse height.

It is important to note that no MCA measures M(E), what is measured is the quantity.

$$M_i = \int_{E_i}^{E_{i+1}} M(E)dE$$

Where $M_i$ = number of counts in the ith channel covering the energy range for $E_i + E_{i+1}$

Hence, one does not measure a continuous function M(E) but a histogram having quantities $M_i$ as shown in the Figure 17.

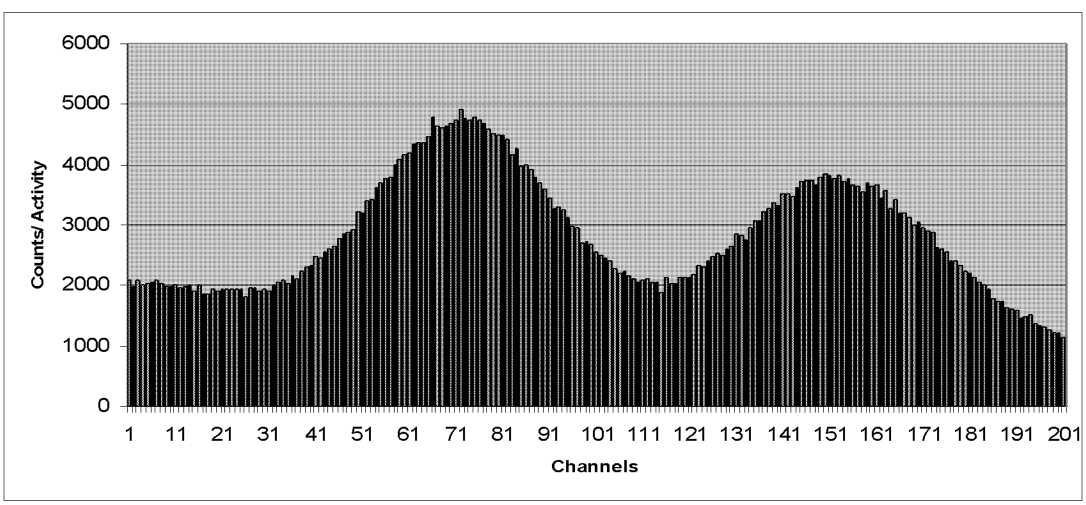


Figure 17. Histogram of unknown isotope.

Figure 17 represents a spectrum for an isotope, the x-axis corresponds to channels ($M_i$) and y-axis is the counts per unit activity.

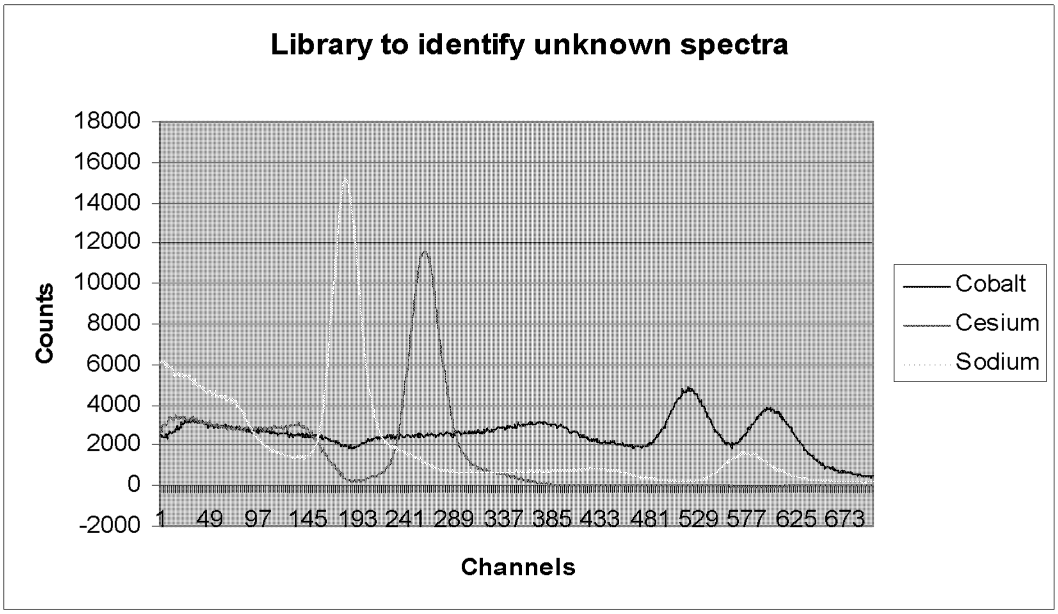


Figure 18. Library isotope spectra used for detection.

From Figure 18, it is clear that the three isotopes considered in this work have peaks at different channels and each is unique. When a data set of an unknown isotope is read to the algorithm, the answer will result in the closest match of the curve in the graph. A sample graph of an unknown isotope is given in Figure 19.

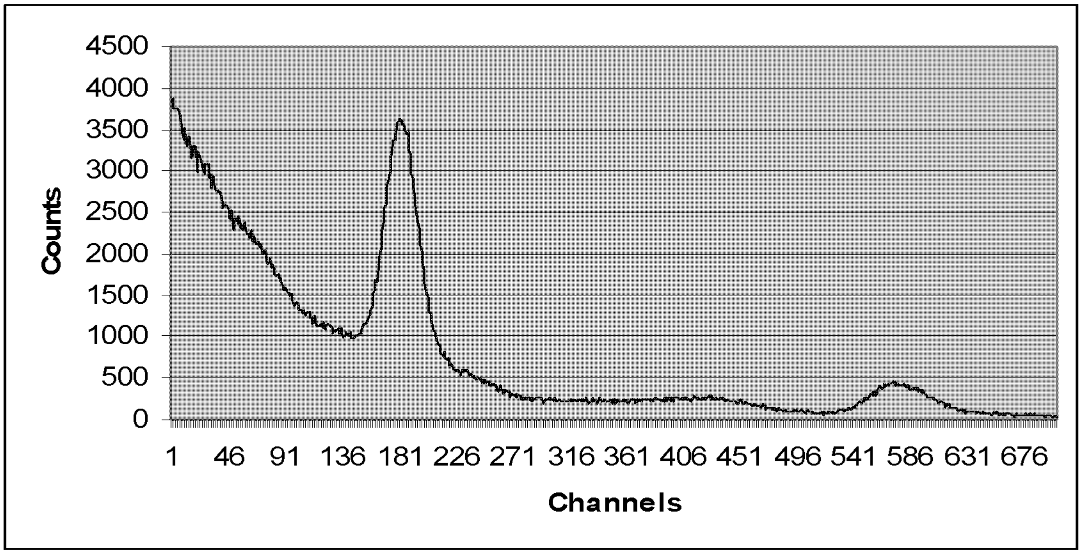


Figure 19. Unknown isotope spectrum.

The matching of this spectrum with the library of isotopes can be visualized in Figure 20.

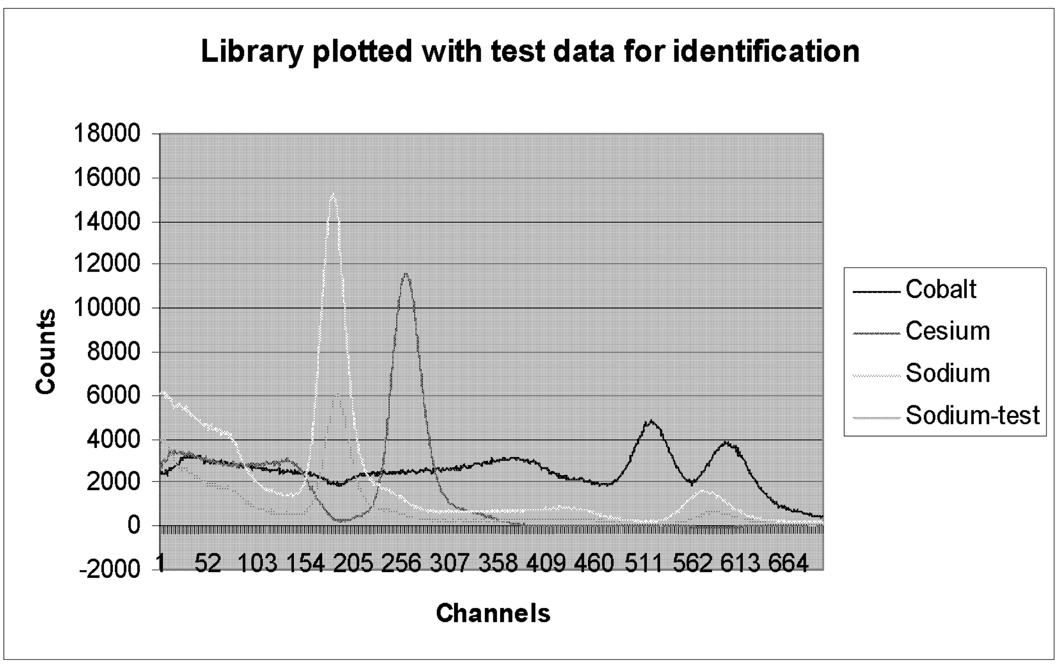


Figure 20. Matching of unknown spectra with the isotope library.

As the graph indicates, the peaks of sodium library data and unknown match with each other. The equations will result in a higher value for this match and will identify the isotope. Due to statistical variation, the activity cannot be calculated accurately. This explains the difference in the heights of the peaks of Sodium library and Sodium test data.

The equations used for regression analysis are on the following page. The variables used are defined in Table 3.

Table 3: Description of variables of equations used for identification of isotope

| Variable | Description |
|---|---|
| O | Counts of unknown isotope read to MATLAB (Vector) |
| M | Counts of known isotopes in the library (Matrix) |
| a | Activity of unknown isotope recognized and calculated (Vector) |

$$O_1 := a_1 \cdot M_{1,1} + a_2 \cdot M_{2,1} + a_3 \cdot M_{3,1} + \ldots\ldots\ldots + a_n \cdot M_{n,1}$$

This equation calculates the total counts in channel 1. This value is equal to the summation of n terms where each term is the product of activity of an isotope in the library of ($a_i$) and the number of counts a unit activity of that isotope would give in channel 1.

Similarly, the value of total counts in channels 2, 3,...,n of the measurement can be found by the following equations.

$$O_2 := a_1 \cdot M_{1,2} + a_2 \cdot M_{2,2} + a_3 \cdot M_{3,2} + \ldots\ldots\ldots + a_n \cdot M_{n,2}$$

-

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$O_k := a_1 \cdot M_{1,k} + a_2 \cdot M_{2,k} + a_3 \cdot M_{3,k} + \ldots\ldots\ldots\ldots + a_n \cdot M_{n,k}$

The total number of channels in this case is 700. A more condensed way of writing these equations is given below.

$$O_1 := \sum_{i=1}^{n} M_{i,1} \cdot a_i$$

$$O_2 := \sum_{i=1}^{n} M_{i,2} \cdot a_i$$

-

-

-

$$O_k := \sum_{i=1}^{n} M_{i,k} \cdot a_i$$

The solution of the isotope activities $a_i$ can be found by formulating the unconstrained linear-least-squares problem.

$$\chi^2 = \sum_{j=1}^{k} (O_j - (\sum_{i=1}^{p} a_i \cdot M_{i,j}))^2 \ \ldots\ldots\ldots\ldots \ \mathrm{I}$$

Where k is the number of channels and p is the number of known isotopes in the library.

Taking the derivative with respect to the activity of the first isotope

$$\frac{\partial \chi^2}{\partial a_1} = 0 = \sum_{j=1}^{k} \{[O_j - \sum_{i=1}^{p} a_i \cdot M_{i,j}][M_{1,j}]\}$$

Simplifying it yields

$$0 = \sum_{j=1}^{k} O_j \cdot M_{1,j} - \sum_{j=1}^{k} M_{1,j} \sum_{i=1}^{p} a_i \cdot M_{i,j}$$

$$\sum_{j=1}^{k} O_j \cdot M_{1,j} = \sum_{j=1}^{k} M_{1,j} \sum_{i=1}^{p} a_i \cdot M_{i,j}$$

Similarly, for isotopes 2 and 3 the derivatives yield.

For isotope 2:

Differentiating equation I with respect to the 2nd isotope

$$\frac{\partial \chi^2}{\partial a_2} = 0$$

$$0 = \sum_{j=1}^{k} O_j \cdot M_{1,j} - \sum_{j=1}^{k} M_{1,j} \sum_{i=1}^{p} a_i \cdot M_{i,j}$$

$$\sum_{j=1}^{k} O_j \cdot M_{2,j} = \sum_{j=1}^{k} M_{2,j} \cdot \sum_{i=1}^{p} a_i \cdot M_{i,j} = 0$$

For isotope 3:

$$\frac{\partial \chi^2}{\partial a_3} = 0$$

$$0 = \sum_{j=1}^{k} O_j \cdot M_{1,j} - \sum_{j=1}^{k} M_{1,j} \sum_{i=1}^{p} a_i \cdot M_{i,j}$$

$$\sum_{j=1}^{k} O_j \cdot M_{3,j} = \sum_{j=1}^{k} M_{3,j} \cdot \sum_{i=1}^{p} a_i \cdot M_{i,j}$$

These equations can be rewritten as

$$\sum_{j=1}^{k} O_j \cdot M_{1,j} = \sum_{j=1}^{k} M_{1,j}(a_1 \cdot M_{1,j} + a_2 \cdot M_{2,j} + a_3 \cdot M_{3,j})$$

$$\sum_{j=1}^{k} O_j \cdot M_{1,j} = a_1 \cdot \sum_{j=1}^{k} M_{1,j} \cdot M_{1,j} + a_2 \cdot \sum_{j=1}^{k} M_{2,j} \cdot M_{1,j} + a_3 \cdot \sum_{j=1}^{k} M_{3,j} \cdot M_{1,j}$$

This method can be expanded to consider any number of isotopes, the number of equations will increase as isotopes are added, which in turn will increase the dimensions of the matrix system used to solve the regression analysis. The equations are written in matrix form below and can be written as:

$$\begin{pmatrix} \sum_{j=1}^{n} O_j \cdot M_{1,j} \\ \sum_{j=1}^{n} O_j \cdot M_{2,j} \\ \sum_{j=1}^{n} O_j \cdot M_{3,j} \end{pmatrix} := \begin{bmatrix} \sum_{j=1}^{n} (M_{1,j})^2 & \sum_{j=1}^{n} M_{1,j} M_{2,j} & \sum_{j=1}^{n} M_{1,j} M_{3,j} \\ \sum_{j=1}^{n} M_{2,j} M_{1,j} & \sum_{j=1}^{n} (M_{2,j})^2 & \sum_{j=1}^{n} M_{2,j} M_{3,j} \\ \sum_{j=1}^{n} M_{3,j} M_{1,j} & \sum_{j=1}^{n} M_{3,j} M_{2,j} & \sum_{j=1}^{n} (M_{3,j})^2 \end{bmatrix} \times \begin{pmatrix} a_1 \\ a_2 \\ a_3 \end{pmatrix}$$

B = A * X

This matrix system is solved to obtain the activities of the isotope by

$X = A^{-1} * B$ Where X is the activity matrix,

A = 3 x 3 response matrix

B = 3 x 1 unknown isotope matrix

The same concept is used to identify the depth and calculation of activity with the difference that now instead of spectra of different isotopes, the evaluation is carried out using response function for each isotope at a given thickness for the unknown measurements.

The equations are developed as shown below

Table 4: Description of variables for activity calculation

| Variable | Description |
|---|---|
| $P_j$ | Counts in channels j |
| $T_{i,j}$ | Response function, Number of counts in channel j due to the isotope activity at depth j |
| $b_i$ | Activity at depth i |

The following equation can be used to calculate the counts at a particular thickness for channel j.

$$P_j = \sum_{i=1}^{h} b_i \cdot T_{i,j}$$

In expanded form, this equation is

$$P_j = b_1 \cdot T_{1,j} + b_2 \cdot T_{2,j} + b_3 \cdot T_{3,j} + \ldots\ldots\ldots\ldots + b_n \cdot T_{n,j}$$

The above equation shows that to calculate counts for a specific channel number, the activities at each depth need to be multiplied by counts in channel j at that depth for a unit activity of the isotope and summed over all depth.

The counts of each channel of the test data are similarly given by the following set of equations derived from the linear least squares fit of

$$\chi^2 = \sum_{j=1}^{o} [P_j - \sum_{i=1}^{o} b_i \cdot T_{i,j}]^2$$

$$\frac{\partial \chi^2}{\partial b_i} = 0 \text{ yields}$$

$$\sum_{j=1}^{n} P_j \cdot T_{1,j} = \sum_{j=1}^{n} T_{1,j}(b_1 * T_{1,j} + b_2 \cdot T_{2,j} + b_3 \cdot T_{3,j} + \ldots\ldots + b_k * T_{k,j})$$

Which is expanded to be :

$$\sum_{j=1}^{n} P_j \cdot T_{1,j} = b_1 \cdot \sum_{j=1}^{n} T_{1,j} \cdot T_{1,j} + b_2 \cdot \sum_{j=1}^{n} T_{2,j} \cdot T_{1,j} + b_3 \cdot \sum_{j=1}^{n} T_{3,j} \cdot T_{1,j} + \ldots\ldots + b_k \cdot \sum_{j=1}^{n} T_{k,j} \cdot T_{1,j}$$

The equations for the remaining channels follow similarly. These equations can be solved by matrix method. The full form of the matrix is shown below.

$$\begin{pmatrix} \sum_{j=1}^{n} P_j T_{i,j} \\ \sum_{j=1}^{n} P_j T_{2,j} \\ \vdots \\ \sum_{j=1}^{n} P_j T_{k,j} \end{pmatrix} := \begin{bmatrix} \sum_{j=1}^{n} (T_{1,j})^2 & \sum_{j=1}^{n} T_{1,j} T_{2,j} & \cdots & \sum_{j=1}^{n} T_{1,j} T_{k,j} \\ \sum_{j=1}^{n} T_{2,j} T_{1,j} & \sum_{j=1}^{n} (T_{2,j})^2 & \cdots & \sum_{j=1}^{n} T_{2,j} T_{k,j} \\ \vdots & \vdots & \ddots & \vdots \\ \sum_{j=1}^{n} T_{k,j} T_{1,j} & \sum_{j=1}^{n} T_{k,j} T_{2,j} & \cdots & \sum_{j=1}^{n} (T_{k,j})^2 \end{bmatrix} \times \begin{pmatrix} b_1 \\ b_2 \\ \vdots \\ b_k \end{pmatrix}$$

The depth identification algorithm is diagrammed in Figure 22. An unknown spectrum (for - µCi Cs-137) was taken at 60 mm as shown in Figure 21. It most closely matches the 90 mm thickness spectrum. The resultant matrix yields a higher value for the 90 mm match and the addition of the three values is the calculated total activity.

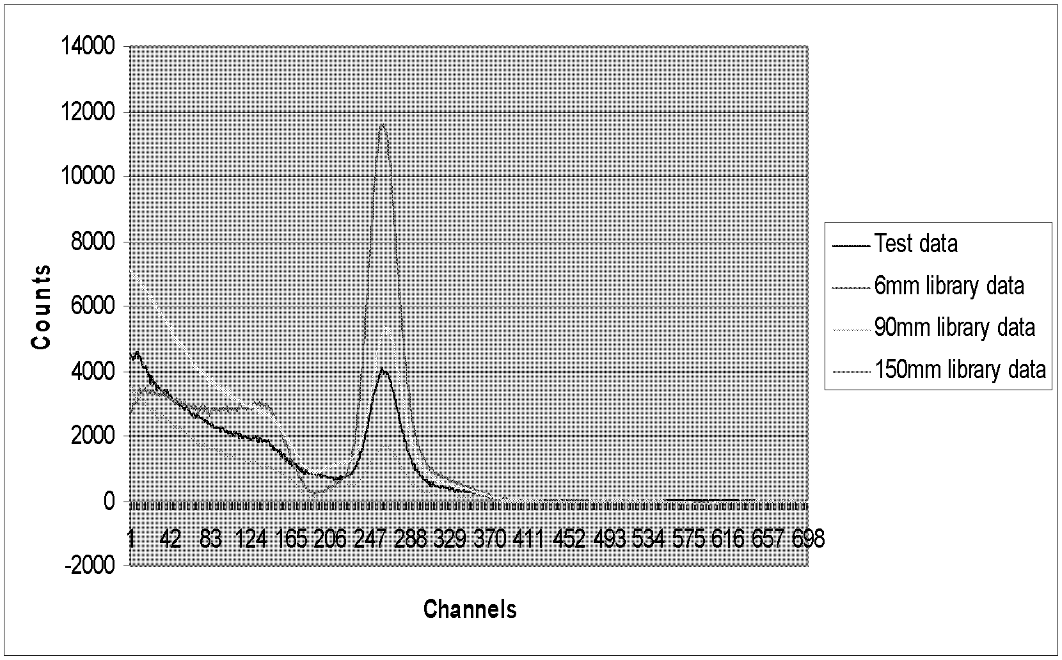


Figure 21. Cs-137 depth identification process.

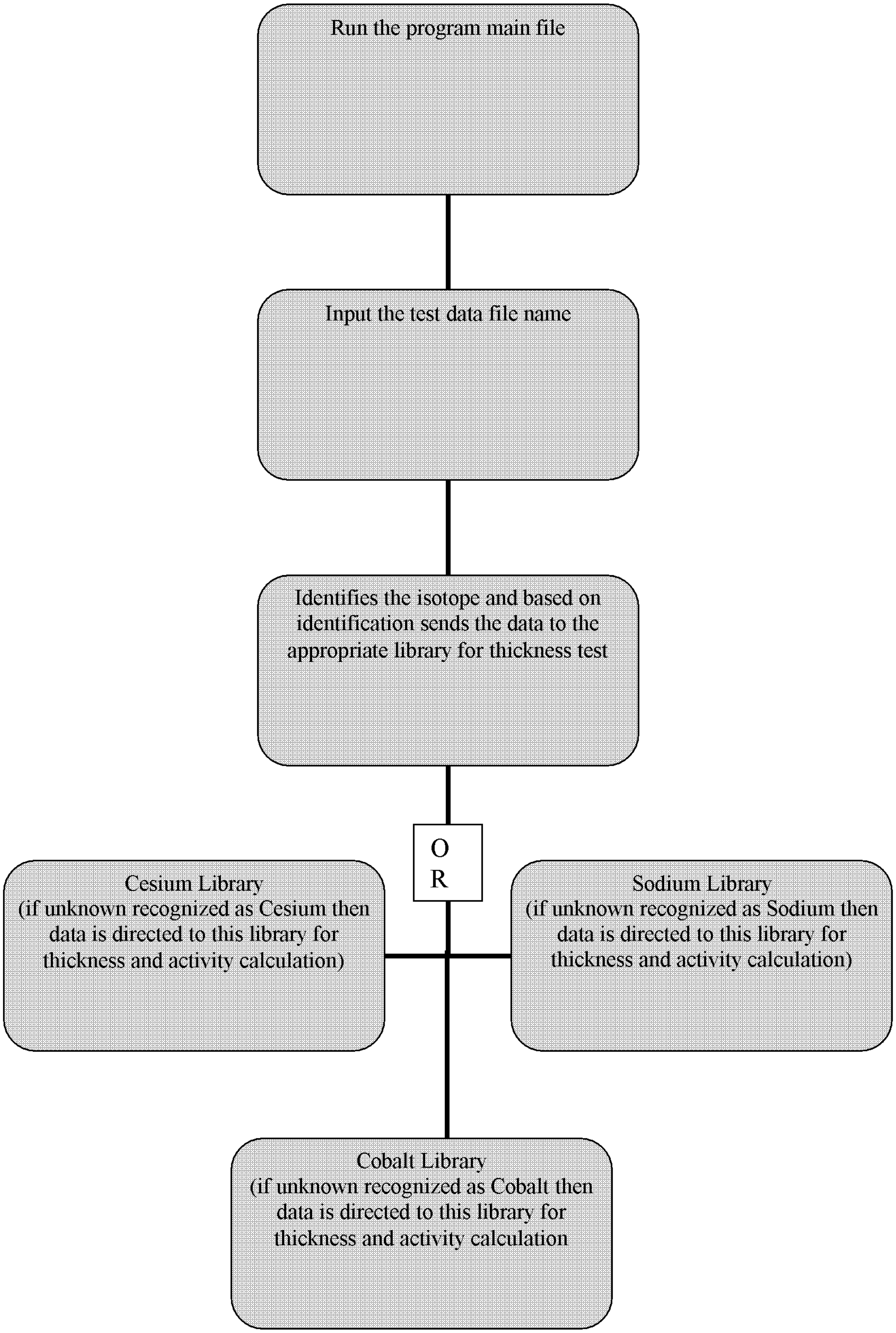


Figure 22. Program Flow Chart.

# Chapter 4

# Results

The Algorithm was tested by initially creating a library of three isotopes (Co-60, Cs-137, Na22) with three thicknesses of 6 mm, 90 mm and 150 mm only. Measured spectrums of these three isotopes at different thickness and activities were tested to check the validity of code. The results and summarized in Tables 5 – 7 and they are discussed in conclusion below.

**Table 5 for Cobalt (Co-60)**

| Isotope | Thickness Tested mm | Thickness Identified mm | Isotope Identified µCi | Actual Activity µCi | Calculated Activity at 6, 90 & 150mm depth | Total calculated Activity | Diff % |
|---|---|---|---|---|---|---|---|
| Co-60 | 6 | 90 | Yes | 0.93 | 0.15, 2.35, -1.81 | 0.69 | 26 |
| Co-60 | 90 | 90 | Yes | 1.13 | -0.03, 1.26, 0.14 | 1.37 | 21 |
| Co-60 | 90 | 90 | Yes | 4.73 | -.27, 13.66, -9.06 | 4.33 | 9 |
| Co-60 | 60 | 90 | Yes | 0.93 | 0, 1.79, -0.53 | 1.26 | 35 |
| Co-60 | 60 | 90 | Yes | 4.73 | 0.03, 3.14, -0.81 | 2.36 | 50 |
| Co-60 | 150 | 150 | Yes | 4.73 | -0.19, -1.68, 5.79 | 3.92 | 17 |
| Co-60 | 150 | 150 | Yes | 1.13 | 0, 0.27, 0.52 | 0.79 | 30 |

**Table 6 for Cesium (Cs-37)**

| Isotope | Thickness Tested mm | Thickness Identified mm | Isotope Identified | Actual Activity µCi | Calculated Activity at 6, 90 & 150mm depth µCi | Total calculated Activity µCi | Diff % |
|---|---|---|---|---|---|---|---|
| Cs-137 | 6 | 6 | Yes | 0.76 | 1.49, -0.73, -0.03 | 0.73 | 4 |
| Cs-137 | 60 | 90 | Yes | 9.1 | 0.03, 6.27, 0.42 | 6.72 | 26 |
| Cs-137 | 90 | 150 | Yes | 1.0 | -0.13, -0.72, 1.65 | 0.8 | 20 |
| Cs-137 | 135 | 150 | Yes | 1.0 | -0.01,-0.71, 1.54 | 0.82 | 18 |
| Cs-137 | 150 | 150 | Yes | 1.76 | 0.00, -0.06,1.63 | 1.57 | 12 |
| Cs-137 | 135 | 150 | Yes | 1.0 | 0.00, -0.01, 0.87 | 0.86 | 14 |

**Table 7 for Sodium (Na-22)**

| Isotope | Thickness Tested mm | Thickness Identified mm | Isotope Identified | Actual Activity µCi | Calculated Activity at 6, 90 & 150mm depth µCi | Total Calc. Activity µCi | Diff % |
|---|---|---|---|---|---|---|---|
| Na22 | 6 | 90 | Yes | 0.93 | 0.03, 0.84, 0.09 | 0.97 | 4 |
| Na22 | 6 | 6 | Yes | 1.85 | 2.86,-0.53,-0.15 | 2.18 | 17 |
| Na22 | 60 | 150 | Yes | 1.85 | 0.23, -1.40, 2.67 | 1.5 | 18 |
| Na22 | 90 | 90 | Yes | 3.0 | 0.37, 2.97, 0.25 | 3.59 | 20 |
| Na22 | 150 | 150 | Yes | 3.0 | 0.20, 1.37, 2.68 | 3.57 | 19 |
| Na-22 | 120 | 150 | Yes | 3.0 | 0.45, 1.37,1.66 | 3.48 | 13 |

.

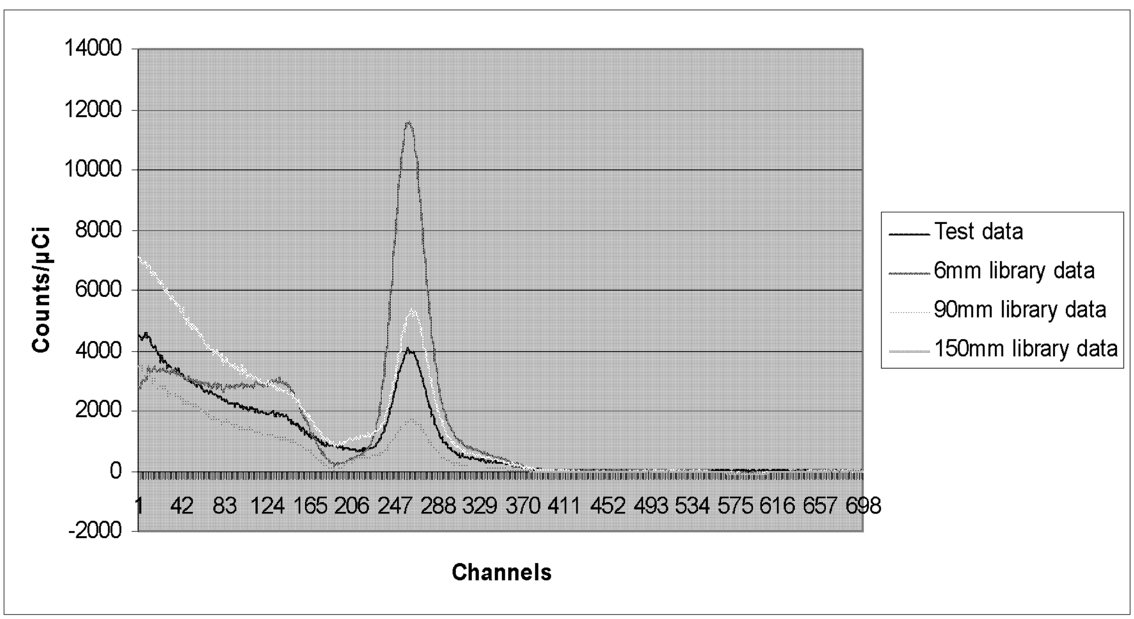


Figure 23. Na-22 spectra plotted with the test data at 6mm thickness

Figure 23 shows that the algorithm calculated the right depth but resulted in an error in activity calculation.

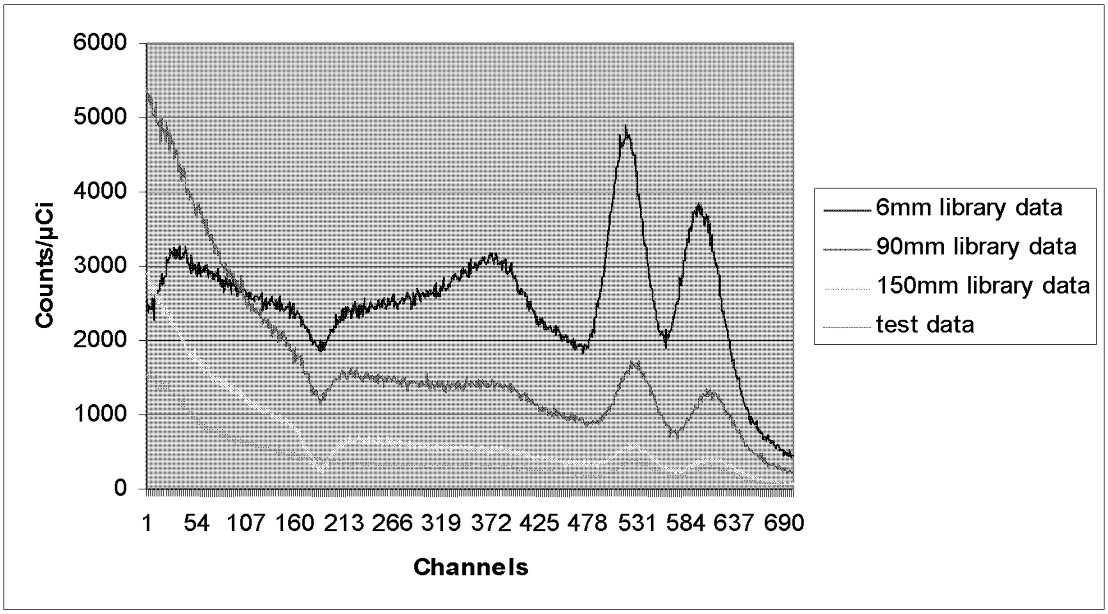


Figure 24. Cobalt thickness library data.

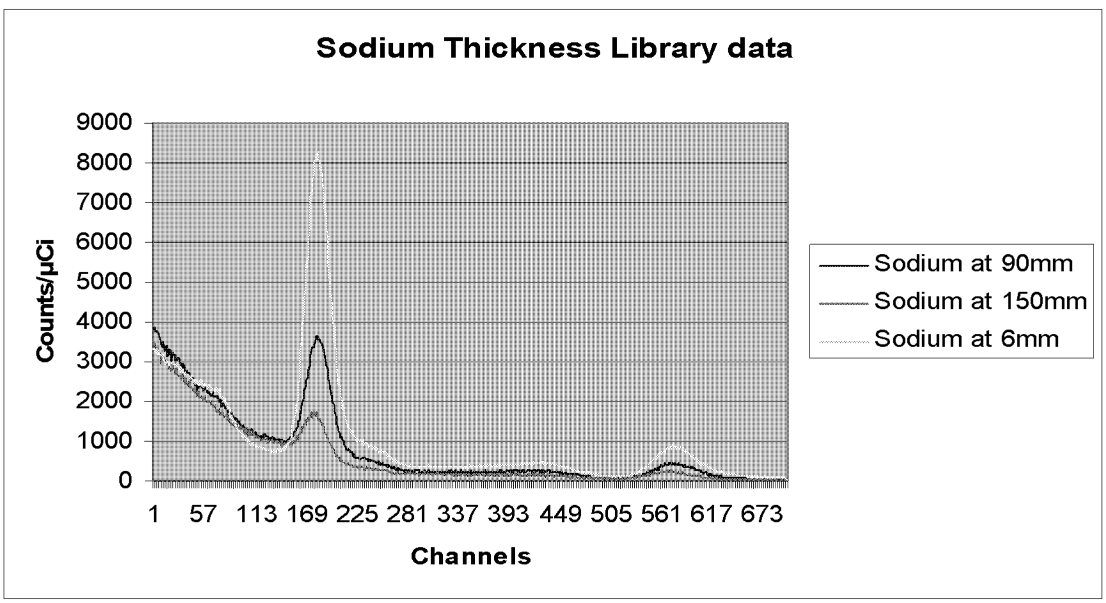


Figure 25. Sodium thickness library data.

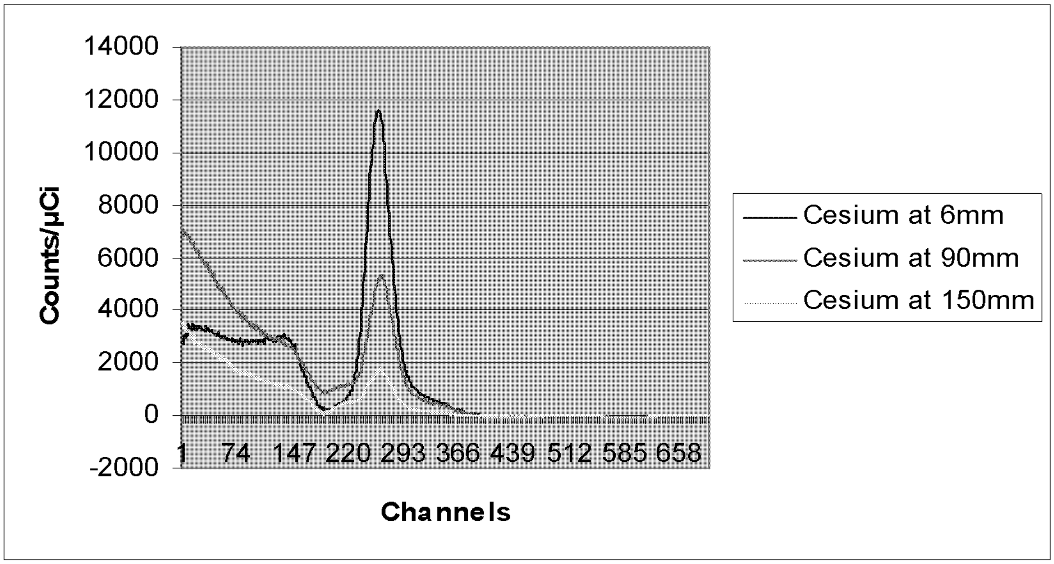


Figure 26. Cesium thickness library data.

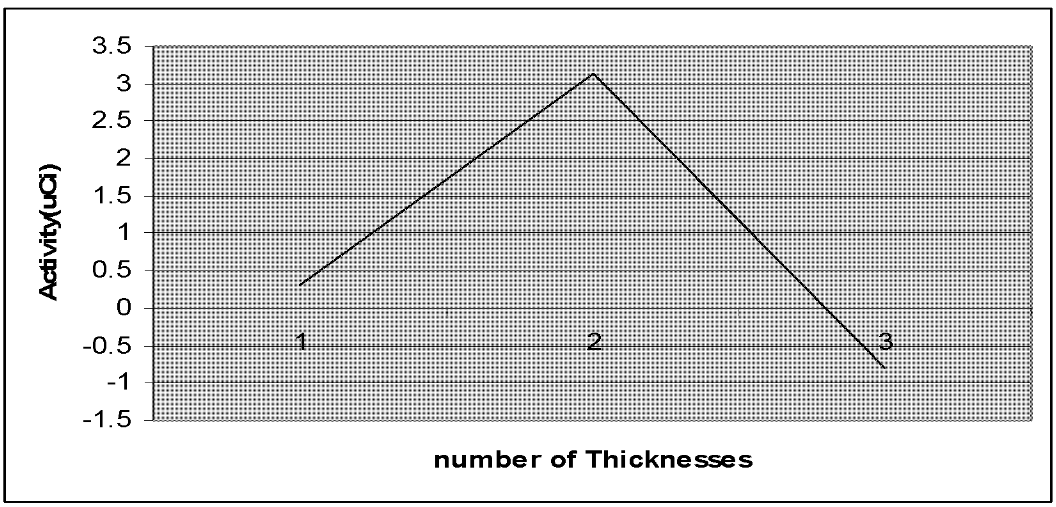


Figure 27. Co-60 4.73 µCi tested at 60mm activity plot.

The graph above plots the three values of activity evaluated by the algorithm. The highest value indicates the right depth and the total of three values is the calculated activity

The screen shot of how the code displays result is shown in Figure 28.

```
enter the file name of the matrix of the unknown isotope(include the extension)?cesium.m

z =

cesium.m


Cobalt =

   -0.0301


Cesium =

    0.3971


Sodium =

    0.1288


ans =

Cesium is the unknown isotope


Cesium_at_6mm =

    0.0762


Cesium_at_90mm =

   -0.1597
```

```
Cesium_at_150mm =

    1.6218


Activity_of_isotope =

    1.5383


ans =

correct thickness is 150mm
```

Figure 28. Screen shot MATLAB Command window.

# Chapter 5

## Conclusion:

The code tested the potential to determine the activity of an unknown isotope internal to a person after a radiological dirty bomb, automatically compensating chest wall thickness. In all the cases, it successfully identified the isotopes present. The code estimated the actual activity of isotopes in the tests with errors ranging from 4% to 30 %.

It must be pointed out that although, the spectra for all the three isotopes were measured at depths of 6, 60, 90, 105, 135 and 150mm Lucite thicknesses. The depths selected for the library only were 6, 90 and 150mm. The reason for choosing three depths instead of six depths was due to over lapping in assigning values to the correct depth during unfolding of algorithm. The code could not recognize marginal differences in thicknesses of Lucite due to little attenuation of photons. Hence, in order for the code to work properly, the difference between the Lucite layers was kept at a minimum of 60mm thickness difference. When the code was tested at depths, which were not in the library, for example at 135mm or 60mm, the code gave the thickness closest to the ones in the library. In the case of 135mm, a 150mm depth was assigned and in the case of 60mm, 90mm depth was assigned. Hence, it is concluded that this set up should only be used as a rough and quick guide to identify the unknown isotope and calculate activity approximately. If, after the RDD incident, a NaI detector identifies and gives approximate activity of an isotope inhaled by a person, the person should be sent immediately for detailed examination if the activity exceeds a threshold value.

# Appendix A

**MATLAB Code**

Data library and Code for identification

To condense space the three data sets are pasted together and the code follows

| A | B | C |
|---|---|---|
| 5399 | 7133 | 1547 |
| 5235.5 | 7031.5 | 1527.5 |
| 5279 | 6842 | 1493 |
| 5296.5 | 6921.5 | 1495.5 |
| 5179.5 | 6892.5 | 1449.5 |
| 5259.5 | 6946.5 | 1474.5 |
| 5015.5 | 6960.5 | 1488.5 |
| 5050.5 | 6779.5 | 1418.5 |
| 5028 | 6715 | 1353 |
| 5188.5 | 6818.5 | 1282.5 |
| 4972.5 | 6791.5 | 1342.5 |
| 4962.5 | 6623.5 | 1347.5 |
| 4892 | 6570 | 1313 |
| 4893 | 6509 | 1328 |
| 5002 | 6604 | 1212 |
| 4669.5 | 6473.5 | 1232.5 |
| 4999.5 | 6582.5 | 1193.5 |
| 4814.5 | 6454.5 | 1226.5 |
| 4857.5 | 6346.5 | 1209.5 |
| 4839 | 6223 | 1150 |
| 4673 | 6215 | 1159 |
| 4959.5 | 6257.5 | 1098.5 |
| 4785 | 6291 | 1113 |
| 4825 | 6105 | 1105 |
| 4552 | 6052 | 1090 |
| 4791.5 | 5968.5 | 1077.5 |
| 4708.5 | 6047.5 | 1070.5 |
| 4652.5 | 5895.5 | 1074.5 |
| 4665 | 5935 | 1083 |
| 4439.5 | 5874.5 | 1058.5 |
| 4507 | 5672 | 1041 |
| 4570 | 5773 | 1018 |
| 4558 | 5814 | 995 |
| 4487.5 | 5776.5 | 990.5 |
| 4282 | 5576 | 993 |
| 4377.5 | 5627.5 | 996.5 |
| 4314 | 5591 | 978 |
| 4138 | 5423 | 995 |

| | | |
|---|---|---|
| 4322.5 | 5585.5 | 950.5 |
| 4203.5 | 5369.5 | 949.5 |
| 4319 | 5262 | 920 |
| 4246.5 | 5286.5 | 936.5 |
| 3991.5 | 5444.5 | 881.5 |
| 4051 | 5105 | 903 |
| 3979 | 5104 | 898 |
| 4005 | 5069 | 916 |
| 3906.5 | 4880.5 | 916.5 |
| 3965 | 5091 | 889 |
| 3950 | 4989 | 838 |
| 3898 | 4772 | 858 |
| 3863 | 4862 | 871 |
| 3778 | 4727 | 807 |
| 3724 | 4879 | 838 |
| 3666 | 4744 | 825 |
| 3817 | 4845 | 779 |
| 3781 | 4673 | 791 |
| 3846.5 | 4740.5 | 769.5 |
| 3794 | 4610 | 756 |
| 3706.5 | 4481.5 | 792.5 |
| 3767 | 4541 | 742 |
| 3647 | 4433 | 779 |
| 3563 | 4537 | 731 |
| 3623 | 4364 | 740 |
| 3531 | 4241 | 733 |
| 3633 | 4241 | 738 |
| 3430 | 4091 | 718 |
| 3496.5 | 4115.5 | 709.5 |
| 3458.5 | 4233.5 | 662.5 |
| 3362.5 | 4055.5 | 707.5 |
| 3416.5 | 4102.5 | 686.5 |
| 3338 | 4017 | 718 |
| 3433.5 | 4005.5 | 687.5 |
| 3186 | 3863 | 728 |
| 3282 | 3950 | 687 |
| 3287 | 3886 | 649 |
| 3266.5 | 4004.5 | 679.5 |
| 3209.5 | 3890.5 | 619.5 |
| 3146 | 3928 | 624 |
| 3192.5 | 3793.5 | 626.5 |
| 3140.5 | 3743.5 | 637.5 |
| 3052 | 3904 | 604 |
| 3028.5 | 3565.5 | 626.5 |
| 3029.5 | 3661.5 | 579.5 |
| 2986 | 3677 | 586 |
| 2932.5 | 3769.5 | 545.5 |
| 3006 | 3574 | 572 |
| 3044.5 | 3633.5 | 559.5 |
| 2797 | 3565 | 551 |

| | | |
|---|---|---|
| 2943.5 | 3469.5 | 559.5 |
| 2942 | 3538 | 526 |
| 2866.5 | 3426.5 | 521.5 |
| 2853 | 3512 | 526 |
| 2931.5 | 3514.5 | 539.5 |
| 2865 | 3344 | 514 |
| 2897 | 3387 | 498 |
| 2742 | 3367 | 526 |
| 2837 | 3454 | 485 |
| 2720.5 | 3233.5 | 513.5 |
| 2808.5 | 3430.5 | 456.5 |
| 2727 | 3519 | 453 |
| 2679.5 | 3219.5 | 482.5 |
| 2763.5 | 3241.5 | 457.5 |
| 2884.5 | 3387.5 | 432.5 |
| 2679 | 3241 | 472 |
| 2796.5 | 3126.5 | 466.5 |
| 2576.5 | 3154.5 | 436.5 |
| 2633 | 3221 | 432 |
| 2564 | 3092 | 443 |
| 2461.5 | 3191.5 | 420.5 |
| 2458 | 3180 | 426 |
| 2542.5 | 3029.5 | 433.5 |
| 2535.5 | 3089.5 | 410.5 |
| 2447 | 3135 | 419 |
| 2393 | 3082 | 415 |
| 2511.5 | 2982.5 | 423.5 |
| 2393 | 3036 | 400 |
| 2390 | 2990 | 380 |
| 2429 | 3033 | 385 |
| 2429 | 2914 | 398 |
| 2383 | 2916 | 365 |
| 2370 | 2913 | 389 |
| 2338.5 | 2939.5 | 380.5 |
| 2435 | 2883 | 351 |
| 2295.5 | 2901.5 | 374.5 |
| 2328 | 2973 | 361 |
| 2269 | 2939 | 366 |
| 2215.5 | 2869.5 | 368.5 |
| 2293 | 2977 | 372 |
| 2299.5 | 2853.5 | 355.5 |
| 2257.5 | 2811.5 | 349.5 |
| 2261.5 | 2897.5 | 344.5 |
| 2309 | 2836 | 329 |
| 2164.5 | 2696.5 | 339.5 |
| 2203.5 | 2746.5 | 322.5 |
| 2226.5 | 2738.5 | 334.5 |
| 2053.5 | 2798.5 | 350.5 |
| 2078.5 | 2630.5 | 337.5 |
| 2210.5 | 2709.5 | 324.5 |

| | | |
|---|---|---|
| 2103 | 2687 | 331 |
| 2147.5 | 2624.5 | 314.5 |
| 2175.5 | 2666.5 | 317.5 |
| 2131 | 2649 | 342 |
| 1982.5 | 2657.5 | 324.5 |
| 2042 | 2556 | 324 |
| 2067 | 2563 | 319 |
| 2115.5 | 2546.5 | 303.5 |
| 1991 | 2561 | 331 |
| 2047.5 | 2590.5 | 329.5 |
| 2127.5 | 2544.5 | 297.5 |
| 2044.5 | 2408.5 | 311.5 |
| 2040 | 2412 | 317 |
| 1937.5 | 2346.5 | 320.5 |
| 1981 | 2304 | 311 |
| 1958.5 | 2362.5 | 313.5 |
| 1943 | 2187 | 306 |
| 1867.5 | 2193.5 | 355.5 |
| 1851.5 | 2039.5 | 331.5 |
| 1876 | 2096 | 319 |
| 1842 | 2067 | 311 |
| 1694.5 | 1993.5 | 347.5 |
| 1892.5 | 2016.5 | 331.5 |
| 1704 | 1880 | 348 |
| 1774 | 1929 | 364 |
| 1804 | 1880 | 372 |
| 1774 | 1717 | 363 |
| 1778.5 | 1791.5 | 378.5 |
| 1799 | 1705 | 406 |
| 1676 | 1661 | 417 |
| 1684.5 | 1605.5 | 423.5 |
| 1726 | 1521 | 470 |
| 1573 | 1460 | 466 |
| 1583 | 1389 | 500 |
| 1553 | 1361 | 525 |
| 1563.5 | 1354.5 | 531.5 |
| 1549.5 | 1323.5 | 565.5 |
| 1542 | 1249 | 565 |
| 1456 | 1229 | 616 |
| 1436.5 | 1105.5 | 627.5 |
| 1301.5 | 1108.5 | 666.5 |
| 1368.5 | 1056.5 | 646.5 |
| 1272.5 | 999.5 | 695.5 |
| 1278 | 1049 | 684 |
| 1316 | 1055 | 688 |
| 1332 | 999 | 691 |
| 1278 | 911 | 716 |
| 1262.5 | 928.5 | 698.5 |
| 1260 | 887 | 730 |
| 1161.5 | 952.5 | 722.5 |

| | | |
|---|---|---|
| 1157 | 861 | 737 |
| 1229 | 874 | 707 |
| 1287.5 | 900.5 | 680.5 |
| 1308 | 922 | 665 |
| 1210 | 823 | 660 |
| 1255.5 | 866.5 | 632.5 |
| 1266 | 930 | 604 |
| 1321 | 920 | 598 |
| 1349 | 906 | 604 |
| 1329.5 | 952.5 | 555.5 |
| 1338 | 954 | 519 |
| 1343.5 | 1008.5 | 516.5 |
| 1396.5 | 984.5 | 444.5 |
| 1388.5 | 1001.5 | 450.5 |
| 1465 | 1053 | 428 |
| 1466 | 1070 | 388 |
| 1491.5 | 1058.5 | 377.5 |
| 1474 | 1093 | 366 |
| 1471 | 1037 | 356 |
| 1472.5 | 1052.5 | 339.5 |
| 1477 | 1070 | 310 |
| 1520.5 | 1104.5 | 287.5 |
| 1578.5 | 1132.5 | 273.5 |
| 1593.5 | 1106.5 | 258.5 |
| 1570 | 1091 | 253 |
| 1541.5 | 1096.5 | 262.5 |
| 1498 | 1175 | 229 |
| 1553 | 1115 | 223 |
| 1531 | 1182 | 241 |
| 1480.5 | 1124.5 | 209.5 |
| 1498 | 1184 | 208 |
| 1585.5 | 1167.5 | 189.5 |
| 1584 | 1178 | 187 |
| 1635.5 | 1236.5 | 186.5 |
| 1547.5 | 1156.5 | 203.5 |
| 1556.5 | 1175.5 | 172.5 |
| 1523 | 1204 | 181 |
| 1597.5 | 1279.5 | 170.5 |
| 1506.5 | 1209.5 | 183.5 |
| 1613 | 1303 | 172 |
| 1564.5 | 1319.5 | 164.5 |
| 1491.5 | 1300.5 | 171.5 |
| 1500.5 | 1342.5 | 177.5 |
| 1516.5 | 1436.5 | 162.5 |
| 1484 | 1467 | 170 |
| 1496.5 | 1444.5 | 158.5 |
| 1460.5 | 1523.5 | 161.5 |
| 1551.5 | 1625.5 | 150.5 |
| 1534.5 | 1667.5 | 165.5 |
| 1497 | 1814 | 151 |

| | | |
|---|---|---|
| 1504 | 1968 | 163 |
| 1568 | 1972 | 171 |
| 1538.5 | 2035.5 | 130.5 |
| 1498 | 2295 | 160 |
| 1482 | 2421 | 145 |
| 1529.5 | 2637.5 | 143.5 |
| 1506 | 2693 | 150 |
| 1516.5 | 2913.5 | 146.5 |
| 1453 | 3028 | 118 |
| 1507.5 | 3246.5 | 133.5 |
| 1453 | 3340 | 139 |
| 1515.5 | 3614.5 | 137.5 |
| 1420 | 3816 | 140 |
| 1553 | 3890 | 122 |
| 1494.5 | 4028.5 | 138.5 |
| 1490.5 | 4341.5 | 124.5 |
| 1510 | 4673 | 116 |
| 1519 | 4644 | 137 |
| 1363.5 | 4868.5 | 121.5 |
| 1476.5 | 4849.5 | 129.5 |
| 1511.5 | 4994.5 | 109.5 |
| 1496.5 | 5126.5 | 118.5 |
| 1449.5 | 5172.5 | 120.5 |
| 1454 | 5206 | 116 |
| 1520.5 | 5360.5 | 98.5 |
| 1464 | 5331 | 104 |
| 1486 | 5157 | 108 |
| 1486 | 5339 | 113 |
| 1443.5 | 5279.5 | 108.5 |
| 1533.5 | 5245.5 | 92.5 |
| 1525 | 5070 | 116 |
| 1457.5 | 5017.5 | 93.5 |
| 1450 | 4956 | 97 |
| 1434 | 4767 | 92 |
| 1488 | 4606 | 98 |
| 1412 | 4408 | 85 |
| 1429.5 | 4184.5 | 98.5 |
| 1473 | 4020 | 92 |
| 1366.5 | 3965.5 | 80.5 |
| 1488 | 3740 | 87 |
| 1445 | 3612 | 86 |
| 1494 | 3383 | 89 |
| 1412.5 | 3155.5 | 84.5 |
| 1425.5 | 3081.5 | 85.5 |
| 1392.5 | 2947.5 | 87.5 |
| 1329 | 2748 | 88 |
| 1445.5 | 2573.5 | 77.5 |
| 1430 | 2455 | 77 |
| 1435 | 2268 | 79 |
| 1445 | 2119 | 82 |

| | | |
|---|---|---|
| 1446.5 | 2006.5 | 79.5 |
| 1419 | 1913 | 79 |
| 1444 | 1780 | 79 |
| 1448.5 | 1671.5 | 76.5 |
| 1428.5 | 1667.5 | 76.5 |
| 1436 | 1486 | 77 |
| 1416.5 | 1463.5 | 79.5 |
| 1376.5 | 1297.5 | 82.5 |
| 1448.5 | 1268.5 | 83.5 |
| 1392 | 1226 | 82 |
| 1403 | 1146 | 76 |
| 1445.5 | 1110.5 | 76.5 |
| 1398 | 996 | 73 |
| 1392 | 968 | 79 |
| 1417.5 | 933.5 | 86.5 |
| 1543.5 | 924.5 | 71.5 |
| 1348 | 877 | 77 |
| 1465.5 | 829.5 | 74.5 |
| 1392.5 | 805.5 | 79.5 |
| 1425.5 | 804.5 | 68.5 |
| 1357.5 | 797.5 | 70.5 |
| 1461 | 780 | 75 |
| 1413.5 | 758.5 | 73.5 |
| 1375 | 672 | 69 |
| 1354.5 | 722.5 | 72.5 |
| 1418 | 683 | 73 |
| 1432.5 | 629.5 | 71.5 |
| 1457.5 | 603.5 | 86.5 |
| 1371.5 | 595.5 | 69.5 |
| 1436.5 | 595.5 | 68.5 |
| 1375.5 | 583.5 | 79.5 |
| 1412 | 610 | 77 |
| 1460.5 | 598.5 | 63.5 |
| 1317 | 609 | 64 |
| 1413.5 | 584.5 | 75.5 |
| 1311.5 | 544.5 | 86.5 |
| 1351 | 550 | 75 |
| 1436 | 505 | 65 |
| 1442 | 509 | 67 |
| 1362 | 502 | 69 |
| 1410.5 | 533.5 | 65.5 |
| 1368.5 | 498.5 | 73.5 |
| 1369.5 | 460.5 | 74.5 |
| 1422 | 484 | 65 |
| 1408.5 | 466.5 | 76.5 |
| 1399 | 448 | 62 |
| 1416 | 426 | 58 |
| 1344 | 456 | 67 |
| 1460.5 | 457.5 | 77.5 |
| 1346 | 445 | 74 |

| | | |
|---|---|---|
| 1365.5 | 449.5 | 71.5 |
| 1440 | 446 | 61 |
| 1355 | 373 | 63 |
| 1345.5 | 349.5 | 70.5 |
| 1406 | 392 | 65 |
| 1319 | 394 | 77 |
| 1368 | 373 | 57 |
| 1429 | 374 | 62 |
| 1495.5 | 383.5 | 69.5 |
| 1424.5 | 322.5 | 70.5 |
| 1392 | 309 | 88 |
| 1426.5 | 362.5 | 61.5 |
| 1401.5 | 332.5 | 62.5 |
| 1377.5 | 289.5 | 77.5 |
| 1446.5 | 308.5 | 65.5 |
| 1423 | 301 | 60 |
| 1435.5 | 304.5 | 65.5 |
| 1396.5 | 304.5 | 60.5 |
| 1411.5 | 277.5 | 63.5 |
| 1462 | 245 | 79 |
| 1381.5 | 223.5 | 81.5 |
| 1397 | 241 | 65 |
| 1467.5 | 254.5 | 54.5 |
| 1355 | 223 | 75 |
| 1461 | 183 | 61 |
| 1424 | 199 | 64 |
| 1469 | 186 | 72 |
| 1412.5 | 153.5 | 63.5 |
| 1403.5 | 191.5 | 69.5 |
| 1438.5 | 168.5 | 57.5 |
| 1384.5 | 141.5 | 74.5 |
| 1364 | 132 | 69 |
| 1420.5 | 138.5 | 69.5 |
| 1363.5 | 109.5 | 68.5 |
| 1382.5 | 148.5 | 65.5 |
| 1393.5 | 126.5 | 61.5 |
| 1455 | 97 | 66 |
| 1468 | 92 | 65 |
| 1458.5 | 78.5 | 62.5 |
| 1354.5 | 103.5 | 63.5 |
| 1410 | 74 | 55 |
| 1422 | 67 | 66 |
| 1417.5 | 65.5 | 66.5 |
| 1437.5 | 65.5 | 67.5 |
| 1428.5 | 49.5 | 71.5 |
| 1379 | 57 | 76 |
| 1379.5 | 39.5 | 64.5 |
| 1408 | 57 | 70 |
| 1357 | 30 | 64 |
| 1417 | 20 | 64 |

| | | |
|---|---|---|
| 1389 | 43 | 66 |
| 1401 | 7 | 71 |
| 1366.5 | 17.5 | 67.5 |
| 1354.5 | 42.5 | 62.5 |
| 1417 | 29 | 63 |
| 1353 | 17 | 68 |
| 1308 | 7 | 66 |
| 1415 | 7 | 64 |
| 1349.5 | 9.5 | 72.5 |
| 1333 | 15 | 70 |
| 1363.5 | 16.5 | 67.5 |
| 1320.5 | 4.5 | 70.5 |
| 1318 | 1 | 68 |
| 1319 | -13 | 68 |
| 1317.5 | -2.5 | 79.5 |
| 1226 | -13 | 71 |
| 1279 | 1 | 69 |
| 1206.5 | 8.5 | 70.5 |
| 1287.5 | 8.5 | 69.5 |
| 1248 | 27 | 61 |
| 1263 | 10 | 66 |
| 1283.5 | 10.5 | 61.5 |
| 1309 | -2 | 66 |
| 1170.5 | 10.5 | 71.5 |
| 1264 | 9 | 61 |
| 1182.5 | -11.5 | 65.5 |
| 1215.5 | 3.5 | 68.5 |
| 1200.5 | -15.5 | 70.5 |
| 1158 | -13 | 69 |
| 1206.5 | -3.5 | 76.5 |
| 1150.5 | 1.5 | 63.5 |
| 1209.5 | 5.5 | 74.5 |
| 1132.5 | -14.5 | 76.5 |
| 1162 | -13 | 73 |
| 1120.5 | -26.5 | 77.5 |
| 1142.5 | 12.5 | 61.5 |
| 1113.5 | -28.5 | 82.5 |
| 1045 | -6 | 60 |
| 1039.5 | -0.5 | 61.5 |
| 1093 | -6 | 74 |
| 1056 | -5 | 72 |
| 1134.5 | -17.5 | 70.5 |
| 1052 | -6 | 67 |
| 1101 | -22 | 64 |
| 1076 | -10 | 64 |
| 1100 | -22 | 69 |
| 1060.5 | -7.5 | 72.5 |
| 1005 | 0 | 66 |
| 1015 | -11 | 70 |
| 1048 | -14 | 63 |

| | | |
|---|---|---|
| 1027.5 | -20.5 | 70.5 |
| 985.5 | -19.5 | 66.5 |
| 996.5 | -10.5 | 66.5 |
| 1136 | -6 | 63 |
| 970.5 | 1.5 | 58.5 |
| 1075.5 | -17.5 | 58.5 |
| 1018 | -1 | 66 |
| 972 | -9 | 69 |
| 1039 | -20 | 65 |
| 1025.5 | 3.5 | 54.5 |
| 1004.5 | -17.5 | 66.5 |
| 963.5 | -15.5 | 62.5 |
| 996 | -20 | 59 |
| 950 | -15 | 59 |
| 1034 | -9 | 57 |
| 938 | -21 | 64 |
| 953.5 | -20.5 | 59.5 |
| 976 | -20 | 63 |
| 933.5 | -28.5 | 54.5 |
| 977 | -15 | 62 |
| 937.5 | -17.5 | 59.5 |
| 959 | -1 | 58 |
| 1020 | -11 | 43 |
| 988 | -21 | 57 |
| 933 | -7 | 56 |
| 1005 | -3 | 50 |
| 893 | -14 | 58 |
| 975 | -6 | 52 |
| 972.5 | -5.5 | 49.5 |
| 951.5 | -19.5 | 51.5 |
| 935.5 | -11.5 | 58.5 |
| 945.5 | -3.5 | 46.5 |
| 921 | -6 | 50 |
| 939.5 | -18.5 | 53.5 |
| 947 | -15 | 53 |
| 943.5 | -8.5 | 46.5 |
| 873 | 12 | 44 |
| 863.5 | -3.5 | 40.5 |
| 910 | -8 | 56 |
| 860.5 | 0.5 | 44.5 |
| 903.5 | -0.5 | 41.5 |
| 881.5 | 2.5 | 41.5 |
| 895 | -4 | 42 |
| 888 | 2 | 41 |
| 872 | -8 | 42 |
| 929 | -4 | 42 |
| 905.5 | -3.5 | 39.5 |
| 888.5 | -1.5 | 34.5 |
| 901 | 7 | 31 |
| 910 | 10 | 39 |

| | | |
|---|---|---|
| 919 | 0 | 37 |
| 890.5 | 2.5 | 32.5 |
| 882 | -6 | 33 |
| 959 | 10 | 32 |
| 942.5 | -1.5 | 36.5 |
| 934 | 8 | 29 |
| 992 | 0 | 43 |
| 945.5 | 14.5 | 32.5 |
| 1003.5 | 7.5 | 34.5 |
| 988 | 6 | 32 |
| 1044 | 3 | 41 |
| 1055.5 | 16.5 | 27.5 |
| 1088 | -6 | 35 |
| 1058.5 | -11.5 | 33.5 |
| 1132.5 | 0.5 | 29.5 |
| 1129 | 0 | 34 |
| 1144 | -4 | 36 |
| 1156.5 | 5.5 | 31.5 |
| 1258 | 5 | 27 |
| 1255 | -10 | 33 |
| 1243.5 | -19.5 | 37.5 |
| 1298 | 11 | 31 |
| 1323.5 | 10.5 | 24.5 |
| 1396 | 11 | 27 |
| 1352 | 4 | 29 |
| 1398 | 2 | 31 |
| 1505 | 10 | 30 |
| 1456.5 | 7.5 | 35.5 |
| 1469 | 15 | 32 |
| 1479.5 | 2.5 | 26.5 |
| 1563 | 2 | 33 |
| 1545.5 | -7.5 | 33.5 |
| 1583.5 | 10.5 | 24.5 |
| 1608.5 | 6.5 | 29.5 |
| 1547 | 7 | 28 |
| 1577 | -2 | 31 |
| 1713.5 | 13.5 | 27.5 |
| 1622.5 | 4.5 | 30.5 |
| 1692 | 3 | 28 |
| 1683 | 13 | 20 |
| 1647 | -1 | 30 |
| 1670.5 | -1.5 | 22.5 |
| 1659 | -5 | 34 |
| 1701 | 3 | 30 |
| 1609.5 | -9.5 | 30.5 |
| 1641.5 | -2.5 | 27.5 |
| 1737.5 | 0.5 | 27.5 |
| 1572.5 | 0.5 | 27.5 |
| 1602 | 0 | 31 |
| 1504 | -2 | 27 |

| | | |
|---|---|---|
| 1578.5 | -2.5 | 27.5 |
| 1542 | 2 | 35 |
| 1467 | -7 | 34 |
| 1462.5 | -8.5 | 33.5 |
| 1443.5 | -10.5 | 32.5 |
| 1413 | -1 | 26 |
| 1413 | 5 | 32 |
| 1366 | -11 | 37 |
| 1265 | -11 | 40 |
| 1332 | 1 | 34 |
| 1298 | -13 | 39 |
| 1262 | -17 | 39 |
| 1231 | -19 | 42 |
| 1144.5 | -14.5 | 38.5 |
| 1125 | -20 | 44 |
| 1083 | -20 | 44 |
| 1021 | 0 | 42 |
| 1074.5 | -26.5 | 49.5 |
| 1008 | -24 | 58 |
| 1002.5 | -9.5 | 37.5 |
| 1008 | -27 | 53 |
| 1002 | -23 | 52 |
| 919 | -21 | 43 |
| 937.5 | -40.5 | 67.5 |
| 852 | -39 | 69 |
| 887.5 | -19.5 | 52.5 |
| 873 | -43 | 69 |
| 884.5 | -35.5 | 62.5 |
| 826.5 | -63.5 | 79.5 |
| 701.5 | -44.5 | 84.5 |
| 794.5 | -51.5 | 73.5 |
| 786.5 | -63.5 | 83.5 |
| 769.5 | -42.5 | 60.5 |
| 780.5 | -52.5 | 79.5 |
| 801 | -54 | 76 |
| 793 | -67 | 90 |
| 678 | -67 | 91 |
| 769 | -66 | 93 |
| 801.5 | -53.5 | 76.5 |
| 804.5 | -73.5 | 96.5 |
| 804 | -61 | 90 |
| 817 | -48 | 81 |
| 812 | -70 | 95 |
| 794 | -74 | 92 |
| 816.5 | -74.5 | 94.5 |
| 871 | -67 | 89 |
| 897 | -79 | 97 |
| 920.5 | -70.5 | 87.5 |
| 942.5 | -79.5 | 94.5 |
| 917 | -84 | 107 |

| | | |
|---|---|---|
| 928.5 | -73.5 | 96.5 |
| 969.5 | -65.5 | 87.5 |
| 1005 | -70 | 88 |
| 1022 | -78 | 97 |
| 1045.5 | -73.5 | 90.5 |
| 1076 | -67 | 92 |
| 1118.5 | -67.5 | 91.5 |
| 1107.5 | -63.5 | 85.5 |
| 1088 | -56 | 77 |
| 1102 | -70 | 83 |
| 1181 | -67 | 78 |
| 1189.5 | -47.5 | 66.5 |
| 1261 | -67 | 87 |
| 1193 | -59 | 88 |
| 1185 | -65 | 84 |
| 1269 | -55 | 79 |
| 1265.5 | -48.5 | 64.5 |
| 1251.5 | -57.5 | 84.5 |
| 1249 | -52 | 68 |
| 1342 | -51 | 65 |
| 1294 | -35 | 55 |
| 1259 | -48 | 66 |
| 1347.5 | -43.5 | 67.5 |
| 1285 | -36 | 57 |
| 1288.5 | -29.5 | 49.5 |
| 1202.5 | -52.5 | 67.5 |
| 1270.5 | -32.5 | 52.5 |
| 1300 | -35 | 57 |
| 1264.5 | -36.5 | 55.5 |
| 1272 | -20 | 48 |
| 1234 | -23 | 40 |
| 1265 | -22 | 46 |
| 1205.5 | -31.5 | 50.5 |
| 1171 | -27 | 44 |
| 1202.5 | -27.5 | 41.5 |
| 1189.5 | -30.5 | 46.5 |
| 1172 | -27 | 46 |
| 1119.5 | -20.5 | 41.5 |
| 1091.5 | -16.5 | 41.5 |
| 1012.5 | -25.5 | 38.5 |
| 1060 | -24 | 44 |
| 1047 | -22 | 41 |
| 1054.5 | -15.5 | 30.5 |
| 975 | -13 | 31 |
| 948.5 | -11.5 | 35.5 |
| 998.5 | -21.5 | 35.5 |
| 852.5 | -7.5 | 29.5 |
| 865.5 | -19.5 | 34.5 |
| 914 | -13 | 32 |
| 857 | -8 | 34 |

| | | |
|---|---|---|
| 793.5 | -11.5 | 26.5 |
| 802 | -7 | 26 |
| 779.5 | -8.5 | 29.5 |
| 747 | -5 | 24 |
| 792.5 | -2.5 | 27.5 |
| 737 | -14 | 30 |
| 729.5 | 0.5 | 17.5 |
| 677.5 | -3.5 | 23.5 |
| 678 | -1 | 21 |
| 671.5 | 0.5 | 18.5 |
| 608.5 | 3.5 | 24.5 |
| 571 | -5 | 23 |
| 585 | -1 | 18 |
| 601.5 | -5.5 | 24.5 |
| 556.5 | 3.5 | 23.5 |
| 530.5 | -7.5 | 23.5 |
| 520.5 | -4.5 | 27.5 |
| 525.5 | -8.5 | 20.5 |
| 509.5 | -2.5 | 25.5 |
| 491 | 3 | 19 |
| 465.5 | -4.5 | 22.5 |
| 478.5 | -5.5 | 22.5 |
| 476 | 3 | 25 |
| 466.5 | -10.5 | 31.5 |
| 434.5 | 3.5 | 21.5 |
| 458.5 | -7.5 | 23.5 |
| 406 | -4 | 24 |
| 466.5 | -7.5 | 24.5 |
| 468.5 | 9.5 | 20.5 |
| 408.5 | 10.5 | 20.5 |
| 370.5 | -4.5 | 26.5 |
| 414 | -6 | 23 |
| 351 | -10 | 30 |
| 341 | 1 | 24 |
| 369 | -5 | 32 |
| 311 | 4 | 27 |
| 361.5 | 4.5 | 22.5 |
| 330 | 7 | 17 |
| 333.5 | -2.5 | 23.5 |
| 321.5 | 2.5 | 18.5 |
| 318.5 | -7.5 | 27.5 |
| 342.5 | 0.5 | 23.5 |
| 303 | -9 | 24 |
| 297 | 5 | 22 |
| 300.5 | -3.5 | 22.5 |
| 273 | 5 | 25 |
| 336 | 5 | 21 |
| 294 | 4 | 18 |
| 266 | 5 | 26 |
| 268 | -1 | 18 |

| | | |
|---|---|---|
| 260 | -1 | 23 |
| 252.5 | -8.5 | 22.5 |
| 260 | 7 | 18 |
| 278 | 1 | 21 |
| 274 | 3 | 20 |
| 266 | 11 | 19 |
| 229 | -1 | 21 |
| 218.5 | -6.5 | 20.5 |
| 238 | -4 | 17 |
| 242 | -1 | 15 |
| 216 | -6 | 17 |
| 231.5 | 15.5 | 19.5 |
| 219.5 | 1.5 | 12.5 |

```
%co60 4.73 µci 90mm

A=[700*1 vector];

A2=A/4.7;%per uci

%Cs 9.1 uci 90mm

B=[700*1 vector];


B2=B/9.1; %per uci activity = 9.1uci


%na22 iuci 90mm march 03

C=[700*1];


C2=C/.9;  %per uci activity = .9

z=input('enter the file name of the matrix of the unknown isotope(include the extension)?','s') %asks for the name of m-file containing test data

z1=load(z); %loads the matrix from the input file as z1

M11=sum(A2.^2); %the following commands compute each term in the response matrix
```

```
M12=sum(A2.*B2);

M13=sum(A2.*C2);

M21=sum(B2.*A2);

M22=sum(B2.^2);

M23=sum(B2.*C2);

M31=sum(C2.*A2);

M32=sum(C2.*B2);

M33=sum(C2.^2);

M=[M11 M12 M13;M21 M22 M23;M31 M32 M33]; %forms a 3x3 matrix

format short

n11=sum(z1.*A2);    % z1 is reading taken from an unknown isotope

n21=sum(z1.*B2);    %forms the matrix with the unknown isotope

n31=sum(z1.*C2);

n=[n11;n21;n31];

X=M\n;   %solve the X = a*inv(b)

format short

Cobalt = X(1,1) %prints the answer in 3 *1 matrix with 1st value as cobalt, 2nd as cesium
and 3rd as sodium

Cesium = X(2,1)

Sodium = X(3,1)

ans = max(X);   %picks the maximum value as the correct answer
```

```
if ans == X(1,1);                %based on the correct answer the loop sends the test data to isotope library for chest thickness evaluation and calculation of activity
'Cobalt is the unknown isotope'
newcobaltthicknessmatrix(z1);
elseif ans == X(2,1);
  'Cesium is the unknown isotope'
  newcesiumthicknessmatrix(z1);
   else ans == X(3,1);
   'Sodium is the unknown isotope'
   newsodiumthicknessmatrix(z1);


end
```

**Code for thickness**

```
function [L] = newcesiumthicknessmatrix(z1)
%cesium thickness file
%cesium thickness 6mm at 1uci
P1=[700 * 1];
CS6=P1;
%cs at 9.1 uci 90mm
P2=[700 * 1 vector];
CS90=P2/9.1;
%Cs 9.1 at 150mm
P3=[700 * 1];
```

```
CS150=P3/9.1;

% unfolding to identify the correct thickness

% Matrix is of the form AX=B In our case, it is WX=U where W is data of the

% library, X is activity in the required thickness and U is data read to

% the library

W11=sum(CS6.^2);W12=sum(CS6.*CS90);W13=sum(CS6.*CS150);

W21=sum(CS90.*CS6);W22=sum(CS90.^2);W23=sum(CS90.*CS150);

W31=sum(CS150.*CS6);W32=sum(CS150.*CS90);W33=sum(CS150.^2);

W=[W11 W12 W13;W21 W22 W23;W31 W32 W33];


U11=sum(z1.*CS6);U21=sum(z1.*CS90);U31=sum(z1.*CS150);

U=[U11;U21;U31];

L=W\U;

Cesium_at_6mm= L(1,1)

Cesium_at_90mm= L(2,1)

Cesium_at_150mm= L(3,1)

Activity_of_isotope = sum(L)

thickness = max(L);

if thickness == L(1,1);

   'correct thickness is 6mm'

elseif thickness == L(2,1);

   'correct thickness is 90mm'

else thickness == L(3,1);
```

```
    'correct thickness is 150mm'
End


function [L] = newcobaltthicknessmatrix(z1)
%P= co 60 thickness
%P1 1uci co 60 6mm thickness
P1=[ 700 x 1 ]
CO6=P1;
%P2=co60 8.9uci at 90mm
P2=[700 x 1]
CO90=P2/4.7;
%Co60 8.9uci at 150mm
P3=[700 x 1 ]
CO150=P3/4.7;


% unfolding to identify the correct thickness
% Matrix is of the form AX=B In our case, it is WX=U where W is data of the
% library, X is activity in the required thickness and U is data read to
% the library
W11=sum(CO6.^2);W12=sum(CO6.*CO90);W13=sum(CO6.*CO150);
W21=sum(CO90.*CO6);W22=sum(CO90.^2);W23=sum(CO90.*CO150);
W31=sum(CO150.*CO6);W32=sum(CO150.*CO90);W33=sum(CO150.^2);
W=[W11 W12 W13;W21 W22 W23;W31 W32 W33];
```

```
U11=sum(z1.*CO6);U21=sum(z1.*CO90);U31=sum(z1.*CO150);

U=[U11;U21;U31];

L=W\U;

Cobalt_at_6mm = L(1,1)

Cobalt_at_90mm = L(2,1)

Cobalt_at_150mm = L(3,1)

activity_of_isotope = sum(L)

thickness = max(L);

if thickness == L(1,1);

    'correct thickness is 6mm'

elseif thickness == L(2,1);

    'correct thickness is 90mm'

else thickness == L(3,1);

    'correct thickness is 150mm'

end


  function [L] = newsodiumthicknessmatrix(z1)

% sodium thickness matrix

% na22 1.85 uci at 6mm thickness data from may 4th

P1=[700 x 1]

NA6=P1/1.85;

% na22 1.85 uci at 90mm from may 4th data
```

```
P2=[700 x 1]

NA90=P2/1.85;

%na22 1.85uci at 150mm thickness from may4th

P3=[700 x 1]

NA150=P3/1.85;


% unfolding to identify the correct thickness

% Matrix is of the form AX=B In our case, it is WX=U where W is data of the

% library, X is activity in the required thickness and U is data read to

% the library

W11=sum(NA6.^2);W12=sum(NA6.*NA90);W13=sum(NA6.*NA150);

W21=sum(NA90.*NA6);W22=sum(NA90.^2);W23=sum(NA90.*NA150);

W31=sum(NA150.*NA6);W32=sum(NA150.*NA90);W33=sum(NA150.^2);

W=[W11 W12 W13;W21 W22 W23;W31 W32 W33];


U11=sum(z1.*NA6);U21=sum(z1.*NA90);U31=sum(z1.*NA150);

U=[U11;U21;U31];

L=W\U;

Sodium_at_6mm = L(1,1)

Sodium_at_90mm = L(2,1)

Sodium_at_150mm = L(3,1)

activity_of_isotope = sum(L)

thickness = max(L);
```

```
if thickness == L(1,1);
    'correct thickness is 6mm'
elseif thickness == L(2,1);
    'correct thickness is 90mm'
else thickness == L(3,1);
    'correct thickness is 150mm'
end
```

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