Radioisotope Identification of Shielded and Masked SNM/RDD Materials

Saleem Salaymeh[1], Ron Jeffcoat[1], Aaron Clare[1], Lane Owsley[2],
Cory Lorenz[3] and Alex Athey[4]
[1]Savannah River National Laboratory, [2]University of Washington,
[3]Johns Hopkins University and [4]University of Texas

ABSTRACT

Sonar and speech techniques have been investigated to improve functionality and enable handheld and other man-portable, mobile, and portal systems to positively detect and identify illicit nuclear materials, with minimal data and with minimal false positives and false negatives. RadSonar isotope detection and identification is an algorithm development project funded by NA-22 and employing the resources of Savannah River National Laboratory and three University Laboratories (JHU-APL, UT-ARL, and UW-APL). Algorithms have been developed that improve the probability of detection and decrease the number of false positives and negatives. Two algorithms have been developed and tested. The first algorithm uses support vector machine (SVM) classifiers to determine the most prevalent nuclide(s) in a spectrum. It then uses a constrained weighted least squares fit to estimate and remove the contribution of these nuclide(s) to the spectrum, iterating classification and fitting until there is nothing of significance left. If any Special Nuclear Materials (SNMs) were detected in this process, a second tier of more stringent classifiers are used to make the final SNM alert decision. The second algorithm is looking at identifying existing feature sets that would be relevant in the radioisotope identification context. The underlying philosophy here is to identify parallels between the physics and/or the structures present in the data for the two applications (speech analysis and gamma spectroscopy). The expectation is that similar approaches may work in both cases. The mel-frequency cepstral representation of spectra is widely used in speech, particularly for two reasons: approximation of the response of the human ear, and simplicity of channel effect separation (in this context, a "channel" is a method of signal transport that affects the signal, examples being vocal tract shape, room echoes, and microphone response). Measured and simulated gamma-ray spectra from a hand-held Radioisotope Identification Device were used to evaluate the algorithms. This paper will present and discuss results of the Test and Evaluation performed on two algorithms produced from the project.

INTODUCTION

Embedded algorithms used in commercial detectors perform poorly at isotope identification in laboratory environments and even worse in the field. Correct isotope identification is less than 35% in commercial detectors under the best conditions (Blackadar et al. (2004)
1, Pibida et al. (2004)2).

The ANSI standard for NaI(Tl) detectors (ANSI Standard 42.34-20033, 42.12-19944) requires an 80% correct identification rate for 10k count gamma-ray spectra and an 80% success of identifying 50-50 mixtures of various isotopes with special nuclear materials (SNM). Both Los Alamos National Laboratory and National Institute of Standards and Technology conducted studies to evaluate the performance of commercial off-the-shelf (COTS) handheld NaI(Tl) detectors and both groups determined that the embedded algorithms in current COTS hardware perform quite poorly compared to the ANSI benchmark (Blackadar et al. (2004), Pibida et al. (2004)). The question arises if this poor performance is a limitation of the modest energy resolution of NaI or if the implemented

algorithms are underdeveloped. In an evaluation of research-grade algorithms Nelson and Sokkappa (2004)5 find that common signal processing methods (template matching, maximum likelihood, principal component analysis) perform vastly better than COTS hardware embedded algorithms. In controlled environments, these research grade algorithms would likely meet the 80% identification rates specified by the ANSI 42.34 and 42.12 standards, however, the authors express concern about the "lack of adaptability to real world conditions," where the algorithms perform much worse (at least 25% lower correct isotope identifications) when subjected to data taken in the field.

If significant additional gains are to be made with radioisotope identification with sodium-iodide detectors, it will probably come from nontraditional signal processing approaches or enabled by new pulse processing technology.

In traditional radioisotope identification signal processing, there are two general approaches that are taken: peak detection or full spectral template matching. Peak detection attempts to deconvolve the instrument resolution and the physical emission, ultimately producing a list of gamma-ray lines and associated intensities. This list of lines is then compared to a database of lines, which can be derived from atomic physics. Full spectral template matching performs a comparison between the observed spectral shape and a composite of spectral shapes from a template library. The template library is typically composed of pure isotopes and backgrounds, and can be generated theoretically or experimentally. In order for either of these detection approaches to be successful with field data, the algorithm must address the "real world modifiers" of background, gain drift, and scattering. There are literally dozens of mathematical methods, pre-processing, and post-processing approaches that can be performed at each step of the peak detection and template matching approaches.

Several well established groups stand out as having produced intriguing concepts and high functioning full spectral radioisotope identification algorithms. R. Estep and B. Sapp at LLNL have been developing the multiple isotope material basis set, MIMBS, for a decade (Estep et al. 19986, Estep & Sapp 2008a7). The MIMBS method simultaneously solves for the isotope producing the radiation and the intervening shielding, addressing the attenuation effect in gamma-ray spectrum analysis. In a similar manner, the MIMBS method has also been applied to the problem of gain drift (Estep & Sapp 2008b). R. Runkle and D. Pfund at PNNL have recently demonstrated the benefits of their algorithm, the nuisance-rejection spectral comparison ratio anomaly detection, N-SCRAD (Pfund et al. 20078, Runkle et al. 20089). The N-SCRAD algorithm was developed to work on a time series of data and employs a thought-out data binning approach coupled with an optimized ROI selection. The ROI selection is designed to maximize SNM detection while minimizing nuisance alarms. D. Stromswold, J. Ely and R. Kouzes and others at PNNL have looked at signal processing in RPMs (both with PVT and NaI(tl)) (Stromswold et al. 200410, Ely et al. 200411, Ely et al. 200612). They show significant gains in SNM versus NORM discrimination via the use of energy windowing. Energy windowing is the subdividing the spectral content into pieces and making comparisons between the ratios of these energy "windows". Finally, T. Gosnell at LLNL and separately K. Nelson and P. Sokkappa at LLNL have investigated and shown the promise of principle component analysis, PCA (Gosnell et al. 199713, Nelson & Sokkappa 200314). Principal component analysis is an analysis method that constructs a set of orthogonal vectors that transform a dataset into basis of maximum variance. Gosnell et al. (1997) setup the framework for PCA radioisotope identification and Nelson and Sokkappa (2003) implemented a PCA "toy model," that worked well in identifying mixtures from a library of synthetic spectra.

This paper discusses the methodology used to develop and test algorithms that accurately identify and classify radioisotopes in areas of higher than normal background and when these nuclear materials may be shielded or masked by attenuation material or other isotopes. Three universities were initially involved with the project, whose goal was to bring successful techniques and features from other areas of signal processing expertise into the field of radioisotope identification using gamma-ray spectroscopy. The primary goal of this project is to develop real time, frequency and statistical analysis algorithms using detection and classification techniques to provide high confidence gamma spectrum analysis for shielded and masked SNM/RDD materials. The Savannah River National Laboratory (SRNL) initially collaborated with three universities in the first phase of the project. After the first year, the University of Texas was down-selected and the two remaining institutions, the University of Washington and Johns Hopkins University, continued algorithm development. A Test and Evaluation (T&E) was conducted with the remaining two universities in year two of the project on April 5-9, 2010. A discussion of the T&E plan and the results of the test will be presented in this report.

SRNL is the lead Principle Investigator, providing support in the areas of nuclear physics, modeling, experimental and field data, algorithm test & evaluation, project management and reporting.

METHODOLOGY

The Savannah River National Laboratory brought the expertise of the passive sonar community to bear upon the more difficult radiation detection and isotope identification tasks encountered in monitoring for SNM/RDD materials in transit. In particular, it is to develop real time, frequency analysis and statistical analysis algorithms based upon established sonar techniques and apply them to gamma spectrum analysis, primarily from data collected by common field instruments at low resolution. The constraints imposed upon the detection and identification of SNM/RDD materials in transit parallel those encountered in passive sonar anomaly detection. Those constraints are as follows: (1) passive data collection with no active interrogation; (2) poor signal-to-noise ratio; (3) abundant interference from legitimate sources; and (4) constantly varying background. The objective is to apply algorithms to accomplish two distinct tasks, detection and identification. Detection will minimize both false positives and false negatives.

The objectives in the first year are to identify the algorithms that show the most promise, demonstrate their performance against spectra taken with common field and laboratory instruments, and benchmark their performance against existing methods and commercial instrument performance. The three laboratories in collaboration with SRNL worked on developing three different algorithms. After the first year one of the labs was down-selected. During the second year the remaining two labs continued to improve their algorithms. A comprehensive algorithm test and evaluation plan was developed by the team to down-select the remaining laboratories.

The T & E consisted of a large number of high-quality gamma-ray spectra that included various levels of background, distances, shielding and combination of radioisotopes. The data set consisted of 446 measured and 829 simulated spectra. The team developed a scoring convention to quantitatively access each of the algorithms and compare the results. The scoring method consisted

of assigning each trial a score based on how accurately the isotope in question was identified. The score was based on the category and the number of isotopes in the spectrum. Table 1 shows the scoring categories and values assigned to each one. A true positive received a score of 10. When more than one result was reported each result was scored. If a result was incorrect, a negative value was assigned to it. The first false positive received a value of -5 and each additional false positive will receive a value of -2. A true positive was defined as detecting an isotope when it was present in the sample and a false positive was detecting an isotope when it was not present in the sample. Also, if a result indicated "SNM Present" when the sample did contain SNM, a score of 3 was assigned. However, when an incorrect result indicated there was SNM present when there was not, then the trial received a -3. The SRNL Principal Investigator was responsible for tabulating the scores and presenting the results. Two scoring examples are described below.

Trial Result	Score Assigned
True Positive	10
First False Positive	-5
Each Additional False Positive	-2
True Positive SNM Present	3
False Positive SNM Present	-3

Table 1: Scoring Criteria

Scoring Example 1:
Suppose the gamma-ray spectrum was from ^{60}Co only. If the algorithm gave the correct answer of ^{60}Co, 10 points was assigned. If the algorithm also reported ^{137}Cs and ^{133}Ba, then -5 and -2 points was also assigned for the first and second false positive results. The final score for this trial was 10-5-2 or a total of 3.

Scoring Example 2:
Suppose a test spectrum was from ^{60}Co and ^{239}Pu. If the algorithm gave the correct answers of ^{60}Co and ^{239}Pu, 10 points was assigned for each true positive (20 points total). If the algorithm also reports ^{137}Cs and ^{133}Ba, then -5 and -2 points would also be assigned for the first and second false positive result. If the report correctly reported the presence of SNM, then 3 points was added to the score. If it reported no SNM present, then -3 points was assigned. If the SNM was reported as being present, the final score for this trial would be 10+10-5-2+3 or a total of 16.

The two algorithms that were subjected to the T & E are described bellow:
The first algorithm was developed in collaboration between SRNL and JHU-APL. It uses support vector machine (SVM) classifiers to determine the most prevalent nuclide(s) in a spectrum. It then uses a constrained weighted least squares fit to estimate and remove the contribution of these nuclide(s) to the spectrum, iterating classification and fitting until there is nothing of significance left. If any Special Nuclear Materials (SNMs) were detected in this process, a second tier of more stringent classifiers are used to make the final SNM alert decision.

The second algorithm was developed in collaboration between SRNL and APL-UW. This algorithm uses a maximum likelihood probabilities classifier. It is looking at identifying existing feature sets that would be relevant in the radioisotope identification context. The underlying philosophy here is to identify parallels between the physics and/or the structures present in the data for the two applications (speech analysis and gamma spectroscopy).

T&E RESULTS AND DISCUSSION

The trials were broken down into six segments or spreadsheets because the application limited the number of columns, and therefore spectra, to no more than 256. Table 2 shows a summary of the number and type of spectra in each segment. Segments 1, 2, 4, and 6 contain spectra simulated by GADRAS. Segments 3 and 5 contain spectra experimentally measured using an Identifinder NGH. The spectra in segments 2, 3, and 6 were generated using only one radioisotope. While segments 1, 4, and 5 spectra could contain up to three isotopes. Each university was charged with identifying the isotopes present in the given spectra using their respective algorithms. Their reported results were then scored using the scoring convention discussed in the methods section. The scores for each university for each segment are shown in Table 3.

From Table 3 it can be seen that both algorithms performed better when given the spectra generated from GADRAS (segments 1, 2, 4, and 6). When given experimentally obtained data (segments 3 and 5) however, the algorithms scored on average over 20% lower than when given spectra simulated by GADRAS.

Test Segment	Isotopes in Spectrum			Bkgd	
	one	two	three	Spectra	Total
1		90	100	38	228
2	182			41	223
3	185			26	211
4	105	35	15	31	186
5	69	105	42	19	235
6	156			36	192
Simulated	443	125	115	146	829
Measured	254	105	42	45	446
Total	697	230	157	191	1275

Table 2: Summary of Spectra for T&E

University	Segment	Score	Total Possible	%
University of Washington	1	4175	4980	83.84
	2	1260	1886	66.81
	3	1136	1946	58.38
	4	1572	2442	64.37
	5	2026	4116	49.22
	6	1060	1560	67.95
	Total	11229	16930	66.33
Johns Hopkins University	1	4181	4980	83.96
	2	1148	1886	60.87
	3	784	1946	40.29
	4	1624	2442	66.50
	5	1735	4116	42.15
	6	1060	1560	67.95
	Total	10532	16930	62.21

Table 3: University Score By Segment

The accurate detection of special nuclear materials is a necessary attribute of radioactive materials identifiers. Table 4 shows the number of accurately detected SNM cases, the number of SNM cases missed and the number of false SNM alarms.

It should be noted that the algorithm employed by the University of Washington did not have an SNM alarm coordinated with the detection of ^{241}Am and ^{238}U. If the university signaled an SNM alarm when it identified these two isotopes, the number of SNM detected correctly would increase from 59 to 127, while the number of false alarms would increase from 12 to 31.

The functionality of each algorithm was tested against both shielded and unshielded isotopes. The figures in Figure 1 show the comparison between the universities using various subsets of data.

University	Segment	SNM Detected Correctly	SNM Missed	SNM False Alarm	Total SNM Present
University of Washington	1	15	45	0	60
	2	0	22	0	22
	3	0	32	5	32
	4	42	43	0	75
	5	2	20	7	22
	6	0	0	0	0
	Total	59	162	12	211
Johns Hopkins University	1	39	21	0	60
	2	5	17	1	22
	3	6	26	4	32
	4	48	37	0	75
	5	1	21	3	22
	6	0	0	0	0
	Total	99	122	8	211

Table 4: SNM Detection

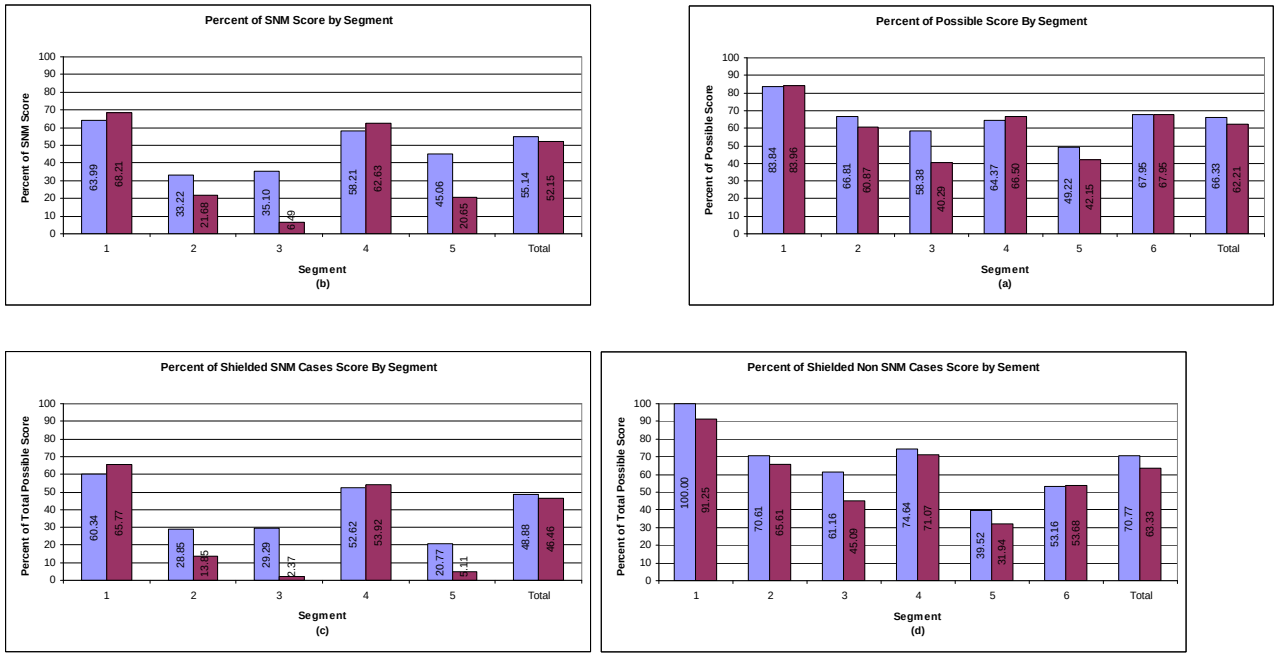

Figure 1 shows the percent score of each university by segment and the total for various subsets of data. The University of Washington is blue and Johns Hopkins University is red. Figure A shows the total score for all types of spectra. Figure B shows the score for all SNM containing spectra. Figure C shows the score for all shielded SNM containing spectra. Figure D shows the score for all shielded non-SNM containing spectra.

For this study, the number of isotopes present in the spectra varied between 1, 2, and 3 isotopes. This data is displayed in Table 5 and Figure 2 below. In the table, the first row in each category is total number of spectra containing 1, 2, or 3 isotopes. The second row is the number that none of the isotopes were correctly identified. The third row is 1 correct, fourth row (pertaining to groups 2 and 3) is two correct and the fifth row (pertaining to group 3) is all three correct. The figure shows the score by percent for each university based on the different number of isotopes present in the spectra.

	University	UW	JHU
One Isotope	Number of Cases	697	697
	Zero Correct	188	214
	One Correct	509	483
Two Isotopes	Number of Cases	230	230
	Zero Correct	8	1
	One Correct	104	101
	Two Correct	118	128
Three Isotopes	Number of Cases	157	157
	Zero Correct	11	12
	One Correct	23	16
	Two Correct	25	41
	Three Correct	98	88

Table 5: Number of Isotopes Correctly Identified

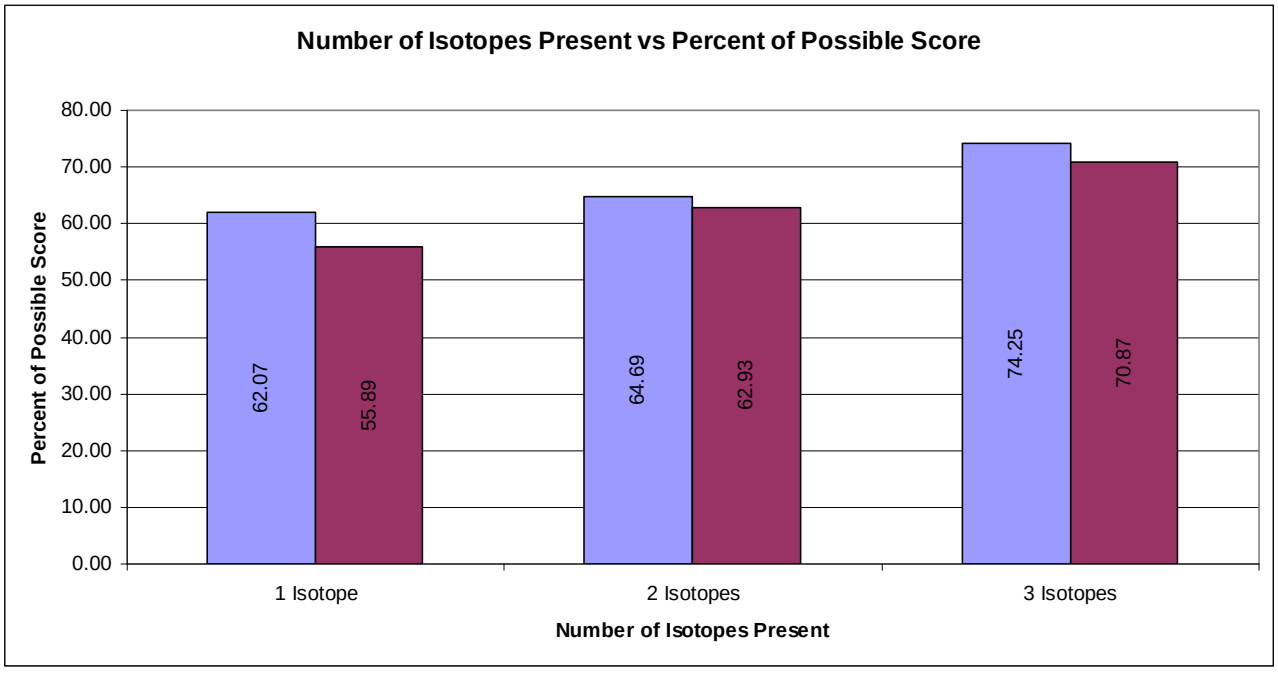

Figure 2: Score Comparison for Different Numbers of Isotopes Present
The University of Washington is in blue and Johns Hopkins University is in red.

CONCLUSIONS

This project resulted in the development of two analysis algorithms for SNM detection and identification. A comprehensive test and evaluation plan and scoring method was developed and a down-select process to one analysis algorithm was completed based on the results of the T & E. The T and E also resulted in a list of improvements that will enhance the robustness of the remaining analysis algorithm. Initial results show an enhanced P_D and lower P_{FA} as compared to what is being used now.

AKNOWLEDEMENTS

The authors would like to thank Drs. Mattingly, Dean Mitchell, and George Lache, SNL for their invaluable discussions and contributions.

REFERENCES

[1] Blackadar, J. M. , Sullivan, C. J., Rees, B. G., Garner, S. E. and Mercer, D. J. "Continuing Evaluation of Isotope Identifiers," proceedings of INMM 45thAnnual Meeting, Orlando, FL, July 18-22, 2004; Los Alamos National Laboratory Publication LA-UR-04-4298.

[2] Pibida, L., Unterweger, M., Karam, L. R., "Evaluation of Handheld Radionuclide Identifiers," Journal of Research of the National Institute of Standards and Technology, vol 109, number 4 pg 451. 2004.

[3] ANSI Standard N42.34, Performance Criteria for Hand-held Instruments for the Detection and Identification of Radionuclides (2003).

[4] ANSI Standard 42.12, American National Standard Calibration and Usage of Thallium-Activated Sodium Iodide Detector Systems for Assay of Radionuclides (1994).

[5] Nelson, K. & Sokkappa, P. "Evaluation of the Effectiveness of Algorithms for Source Identification" in "Foundations for Improvements to Passive Detection Systems - Final Report," Lawrence Livermore National Laboratory Publication UCRL- TR-207129, pp. 47-71. Oct, 2004.

[6] Estep, R.J.; Rawool-Sullivan, M.; Miko, D., "A method for correcting NaI spectra for attenuation losses in hand-held instrument applications," IEEE Transactions on Nuclear Science, vol.45, no.3, pp.1022-1028, Jun 1998.

[7] Estep, R.J.; Sapp, B.A., "The Multiple Isotope Material Basis Set (MIMBS) Method for Handheld Instrument and Portal Monitor Isotope Identification," proceedings of the 8th International Conference on Facility Operations-Safeguards Interface, March 2008a.

[8] Pfund, D.M.; Runkle, R.C.; Anderson, K.K.; Jarman, K.D., "Examination of Count-Starved Gamma Spectra Using the Method of Spectral Comparison Ratios," Nuclear Science, IEEE Transactions on , vol.54, no.4, pp.1232-1238, Aug. 2007.

[9] Pfund, D.M.; Runkle, R.C.; Anderson, K.K.; Jarman, K.D., "Examination of Count-Starved Gamma Spectra Using the Method of Spectral Comparison Ratios," Nuclear Science, IEEE Transactions on , vol.54, no.4, pp.1232-1238, Aug. 2007.

[10] Stromswold, D.C.; Darkoch, J.W.; Ely, J.H.; Hansen, R.R.; Kouzes, R.T.; Milbrath, B.D.; Runkle, R.C.; Sliger, W.A.; Smart, J.E.; Stephens, D.L.; Todd, L.C.; Woodring, M.L., "Field tests of a NaI(Tl)-based vehicle portal monitor at border crossings," Nuclear Science Symposium Conference Record, 2004 IEEE , vol.1, no., pp. 196-200 Vol. 1, 16-22 Oct. 2004.

[11] Ely, J.H.; Kouzes, R.T.; Geelhood, B.D.; Schweppe, J.E.; Warner, R.A., "Discrimination of naturally occurring radioactive material in plastic scintillator material,", IEEE Transactions on Nuclear Science, vol.51, no.4, pp. 1672-1676, Aug 2004.

[12] Ely, J., Kouzes, R., Schweppe, J., Siciliano, E., Strachan, D., Weier, D, "The use of energy windowing to discriminate SNM from NORM in radiation portal monitors", *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, Volume 560, Issue 2, 10 May 2006, Pages 373-387.

[13] Gosnell, T. B., LLNL Hall, J. M. Jam, C. L. Knapp, D. A. Koenig, Z. M. Luke, S. J. Pohl, B. A. Schach von Wittenau, A. Wolford, J. K., "Gamma-ray identification of nuclear weapon materials," Lawrence Livermore National Laboratory Publication UCRL-ID-127436, February, 1997.

[14] Nelson, K. private communication, 2003. Reported in "Source Simulations," Wurtz, R., Pohl, B. and Frank, M. in "Foundations for Improvements to Passive Detection Systems - Final Report," Lawrence Livermore National Laboratory Publication UCRL- TR-207129, pp. 47-71. Oct, 2004.