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Cadmium-Zinc-Telluride (CZT) Gamma Ray Spectrometry

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SPECIAL TECHNOLOGIES LABORATORY
Santa Barbara, California

DISCLAIMER

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CONTENTS

INTRODUCTION

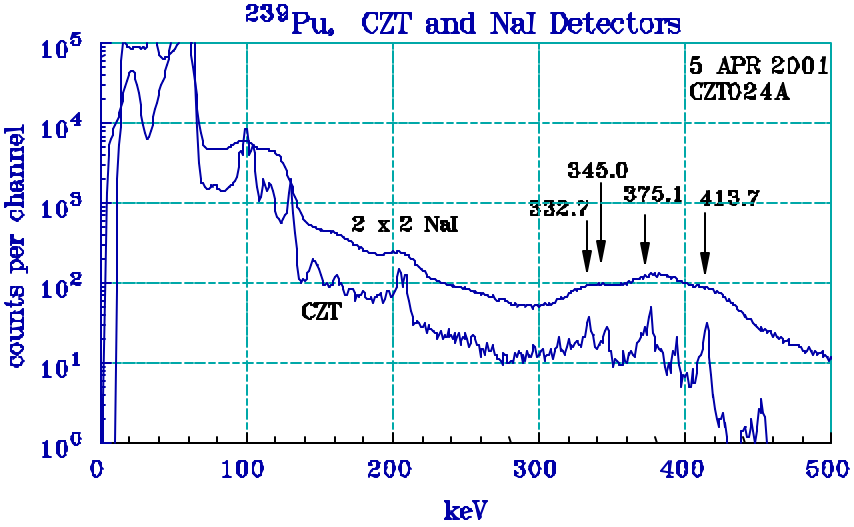
Isotope Identification via Gamma Ray Spectroscopy

Gamma ray spectroscopy is a measurement technique that permits identification of specific isotopes by recording the energy of the gamma rays emitted by the isotope. For example ^{235}U may be identified by the presence of 185 keV gamma rays.

These gamma rays are detected and their energy determined by recording their interaction with special instruments called gamma ray spectrometers. A spectrometer consists of a detector that produces an electrical response for each gamma ray interaction and some means of recording this response electronically. An analysis of these recorded responses results in quantification of the gamma ray energy causing the response. This gamma ray energy information can then be used to identify the isotope responsible, i.e., isotope identification.

There are several types of gamma ray spectrometers commercially available. They differ markedly in the hardware necessary for their support. For example some spectrometers require liquid nitrogen for detector cooling. Other spectrometers may have large room temperature detectors with very high efficiency. Newer solid state detectors can also operate at room temperature.

In all cases the energy resolution of the detector used in the gamma ray spectrometer is an important parameter. A detector showing very good energy resolution will enable determination of the gamma ray energy with little error. This leads to a more secure isotope identification. An example illustrating the consequences of widely differing energy resolution is shown in the figure below taken from Appendix A. In this example the Cadmium-Zinc-Telluride (CZT) spectrum shows several peaks that can be easily associated with a unique energy and thus identify the isotope as ^{239}Pu. The 2×2 sodium iodide (NaI) spectrum on the other hand has only a hint that the elevated counting rates in the 400 keV region have a unique underlying structure that could be used for isotope identification.



CZT, a Room-Temperature High-Resolution Gamma Ray Detector

CZT crystals are one of the few room temperature solid-state gamma radiation detectors commercially available. This material can provide gamma ray spectra suitable for isotope identification.

CZT has several advantages: room temperature operation and hence no need for liquid nitrogen or Peltier coolers; very high atomic number and high density leading to a good intrinsic detection efficiency; and sturdy detectors that can be packaged compactly in a rugged field instrument.

There are several disadvantages however, the most important being small size. The ternary CZT crystals thus far available are limited in size due to physical problems during growth. This small detector size (we use crystals that are 5-mm cubes) produces a low counting rate compared to other larger detectors and thus requires a longer counting time for equal statistical precision.

The small crystal size also limits the high energy gamma response since higher energy gammas, above 600 keV for example, will have a low interaction probability and will produce a significantly lower counting rate compared to gammas of, say, 300 keV. This limitation is not all bad however because it applies to background as well. As an example, the common background isotope, ^{40}K, has a gamma peak of 1460 keV which is detected with very poor efficiency. This poor background counting rate and results in a better signal to noise ratio for CZT compared to physically larger detectors. This improves the Minimum Detectable Activity (MDA) for those gamma peaks less than 600 keV.

The CZT crystals do not require extensive environmental protection; they are light sensitive, but not affected by moisture, so simple packaging is possible. This can be used to advantage in construction of miniature detector packages. The simplified packaging needs have also enabled development of CZT arrays to improve the overall sensitivity. The current array of eight individual crystals is an example of this form of packaging.

Support Funding

Initial funding for the CZT array development was provided by the Office of Intelligence (IN-1), Special Technology Program (STP) of the U.S. Department of Energy. Subsequent funding was provided by the U.S. Customs Service for a portable hand-held instrument. Other government agencies provided funding for other instrument designs.

OVERVIEW OF DOCUMENT

This report describes CZT crystals and their use in large arrays for generation of gamma ray spectra. Laboratory spectra will be shown together with spectra accumulated by various battery powered portable instruments (see Appendix A). One of these portable instruments was specifically constructed to minimize power consumption and yet provide reasonable isotope identification capability.

Detailed data will be presented covering gamma energy resolution, gamma peak shapes, system background, and detector efficiency. Nearly all data were taken with very small crystals of CZT; cubes 5 mm on a side. A few spectra will be presented from cylindrical crystals of about the same size (see Appendix A).

The small crystal size leads to low counting rates and extended counting times for reliable isotope identification. We have addressed this problem by using arrays of CZT crystals, initially two crystals and, at present, arrays of eight crystals. Data will be shown relating spectral parameters for these two arrays.

System MDA is one way of combining resolution, efficiency, and background that will enable direct comparison of various detector types for individual isotope identification. We have calculated the MDA for an early dual crystal array and the current eight crystal array. Data derived from each array will be presented. In addition, it is possible to extrapolate the MDA methodology to much larger arrays. A 32-crystal array is under construction and extrapolations to 256 and 1024 crystals are considered possible. Estimated MDA values for these larger arrays are also presented.

Several 8-crystal arrays have been constructed and versions have been incorporated into portable instruments. Descriptions of these small instruments are given covering physical size, weight, and general configuration. These instruments have been tested for shock and temperature effects and data will be presented on the results of these tests.

The MDA concept will also allow extrapolation to large source to detector distances. The usual laboratory measurements are done with small sources at 20 to 50 cm ranges. Practical ranges for aerial work will be 50 to 100 meters or greater. These distances will require correction for air attenuation for most of the low energy isotopes. The approximations used in the present note for aerial measurements involve small diameter sources (diameter approximately equal to the altitude), a 1 kt pass, and a planar array with no aircraft attenuation material in the field of view. The array will have a collimator to limit the side-looking sensitivity to enable a more accurate extrapolation from the laboratory data.

Large arrays will have significant physical size and weight compared to the small hand-held instruments thus far constructed. We estimate these parameters and extrapolate the power consumption to provide a realistic estimate of a suitable airborne system. In all cases these larger systems are lighter and physically more compact than the usual NaI or high purity Germanium (HPGe) systems used in aerial work. Thus deployment should be simple. The power consumption is much less as well.

ENERGY RESOLUTION, GAMMA PEAK WIDTH, BACKGROUND, AND EFFICIENCY

Energy Resolution

CZT crystals have been used at Special Technologies Laboratory since late 1998. The hardware has evolved from simple hand wired laboratory test devices to the current 8-crystal arrays. The comparison shown in Figure 1 was typical of the early hand wired devices using just two CZT crystals. This dual crystal detector was eventually compared with early versions of the 8-crystal array and the resolution found to be identical. This comparison presents measured data for two common scintillators, a 2×2 and a 3×2, and three types of solid-state detectors. The CZT data are derived from measurements on both a 2- and an 8-crystal array. In general, the smaller the resolution the more easily the detector can be used for isotope identification.

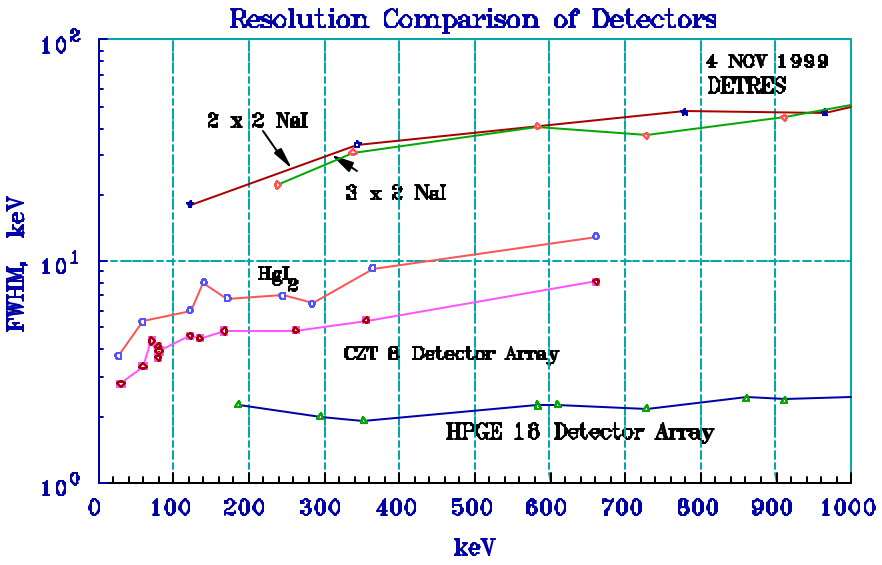


Figure 1. Resolution comparison between several detector types.

In each of the data sets shown the detectors were powered with laboratory power supplies, and NIM-BIN amplifiers and Multichannel Analyzers (MCAs) were used for data collection and analysis. In this original work the CZT crystals were arranged in pairs that were paralleled into one analog preamplifier. This increased the resolution slightly, but made the laboratory test fixtures much more compact. The ultimate goal was creation of a small detector incorporating at least eight crystals.

The CZT crystal arrays were subsequently modified for lower power and a Cockcroft-Walton high-voltage power supply (HVPS) was designed for the unit. Additional modifications incorporated a miniature Geiger-Mueller (G-M) tube for exposure rate estimations that used the same power supply. Lastly the power consumption was reduced by paralleling six crystals (all that were available at the time) into one analog preamp. This made the resolution worse, but cut the analog power by approximately 60%. Each of these modifications compromised the resolution somewhat to reach the goal of a small battery-powered instrument. The following

figures show the resolutions found for the battery-operated instruments. It is expected that there may be some improvement in the future.

Figure 2 presents the resolution found for a 6-crystal array in a battery-powered instrument compared to the CZT data in Figure 1. It is clear that there is a factor of approximately 2 degradation in peak resolution. As noted above this is due to a combination of HVPS noise, and low power circuitry for the analog and digital hardware.

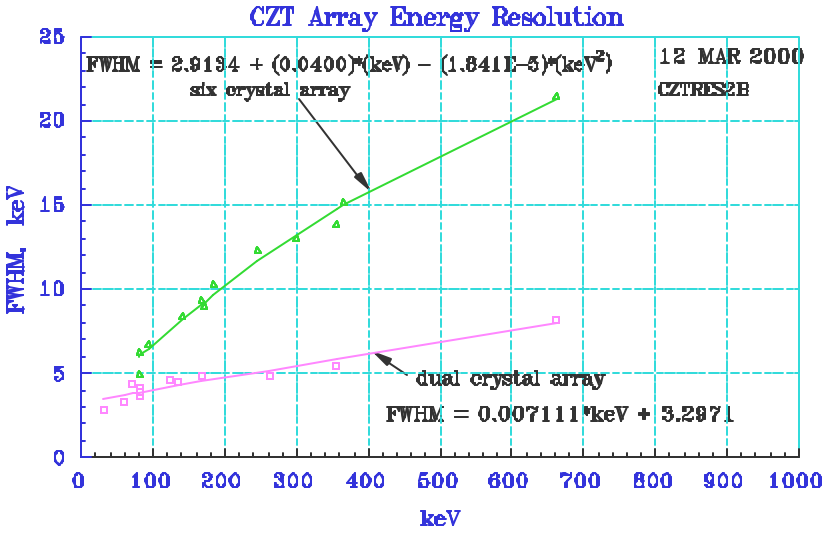


Figure 2. Resolution comparison, 6-crystal array and 2-crystal array.

A similar set of crystals was incorporated into an improved battery-operated device resulting in better energy resolution. Figure 3 presents these data for a 6-crystal array compared to the MAR 2000 data and the original 2-crystal data.

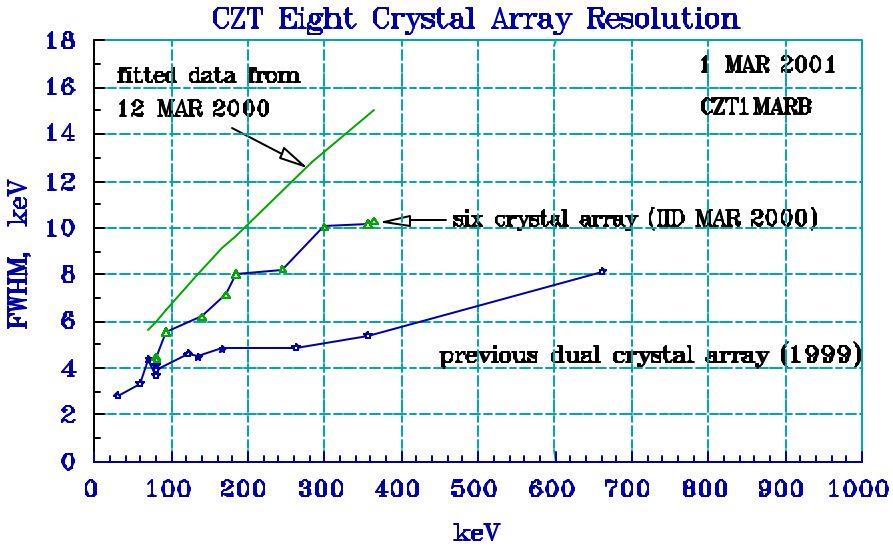


Figure 3. Resolution in improved battery operated instrument.

Figure 4, below, presents a comparison between the same set of four crystals when used with an external NIM-BIN analog to digital converter (ADC) and when used in a portable instrument originally designed for the U.S. Customs Service. This instrument was very complex with five ADCs (four for the CZT and one for the NaI scintillator), a 2 × 2 NaI scintillator, two ^{3}He tubes, a G-M tube, three separate HVPSs, isotope identification software, an LCD display, and two processors. One result of this complexity was an increase in noise level and a degradation in resolution. The instrument operated well despite the noise increase and identified 18 different isotopes and some mixed isotope combinations.

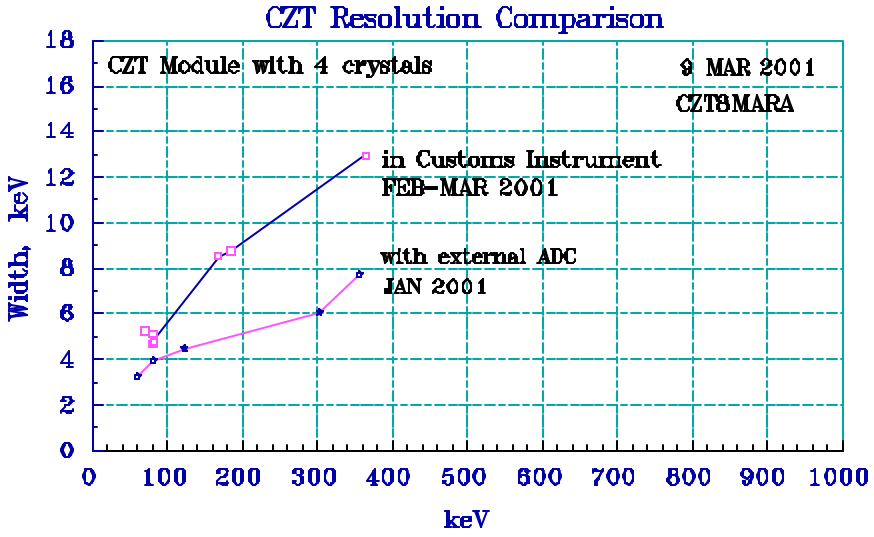


Figure 4. Comparison between NIM hardware and a battery operated instrument.

Gamma Peak Width

The energy resolution parameters shown in the previous section are an important measure of a detector's utility in isotope identification. It was shown that a portable battery operated instrument will have a full width-half maximum (FWHM) that varies from approximately 4 to 13 keV over the energy range from 60 to 400 keV. While this single parameter provides valuable information about the detector's performance it is not enough to permit calculation of the MDA. This section will discuss one way that the MDA can be determined from spectroscopic data. The MDA will permit estimation of detection capability *versus* energy and for various distances.

A gamma peak must stand out from the background continuum for this peak to be found and quantified. The criterion used in this paper requires the net counts in the peak to be at least three times the standard deviation of the background in the peak region. The peak region used for the determination of background is FW50M or the full width at 1/50 the peak height. This parameter is slightly larger than the width selected visually. The FW50M has the advantage that most commercial analysis software can determine this value automatically. Thus the net counts in a peak are those counts remaining after the background is subtracted from the gross counts, all within the FW50M region around the peak location. Three standard deviations of the background over this same region are then compared to the net counts, and a peak is declared if the net counts exceed the 3σ value.

The FW50M is energy dependant and is similar in shape to the FWHM curve, but much larger. Figure 5 presents FW50M data for a dual crystal array with laboratory electronics.

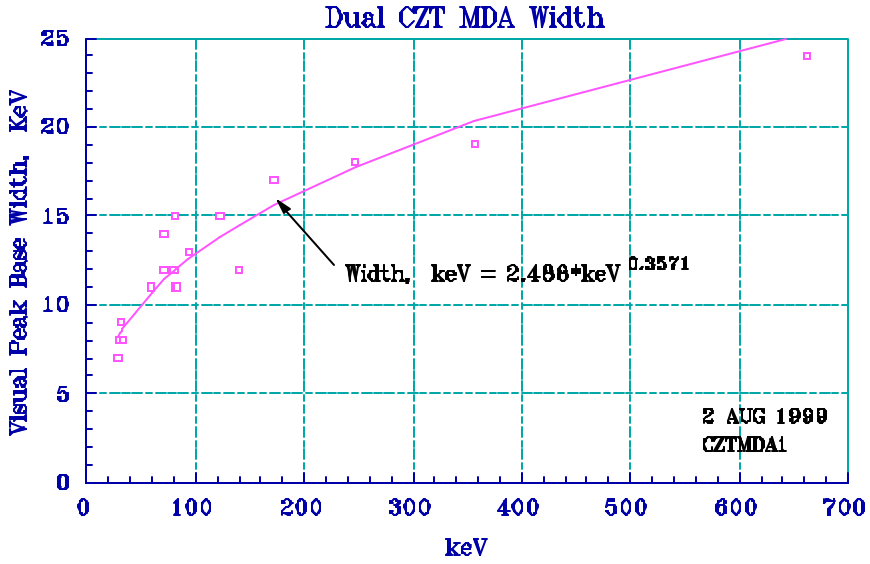


Figure 5. Visual peak width in keV for a dual crystal array.

When eight crystals are used in a battery-operated array the FWHM was found to increase, and the FW50M increases as well. The data in Figure 6 show measurements taken with the U.S. Customs Service instrument and a large variety of common medical isotopes and industrial sources. The increase in width from laboratory electronics to battery powered gear is approximately a factor of two.

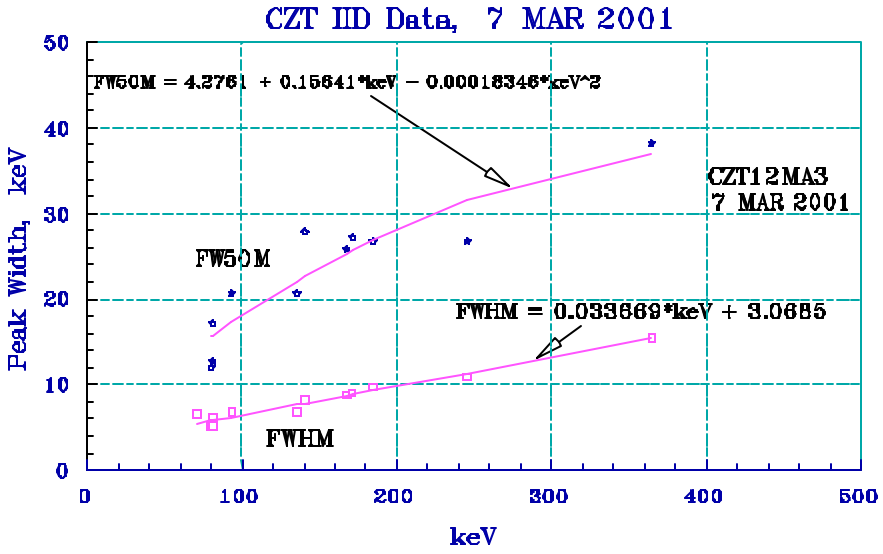


Figure 6. FWHM and FW50M peak widths for an 8-crystal array.

Part of the degradation in FW50M as well as FWHM is due to less rigorous selection of CZT crystals for the 8-crystal array (there were a limited number available), and the noisy instrument environment. This instrument used four ADCs for the CZT analysis and had the eight crystals arranged in pairs. The four spectra were digitally summed after individual gain and offset corrections were made. This process did not contribute significantly to the spectral degradation.

Instrument Background

The instrument background is shown in Figure 7, below, for an early dual crystal design. The background shape does not change significantly, but the magnitude depends upon the number of crystals in the instrument.

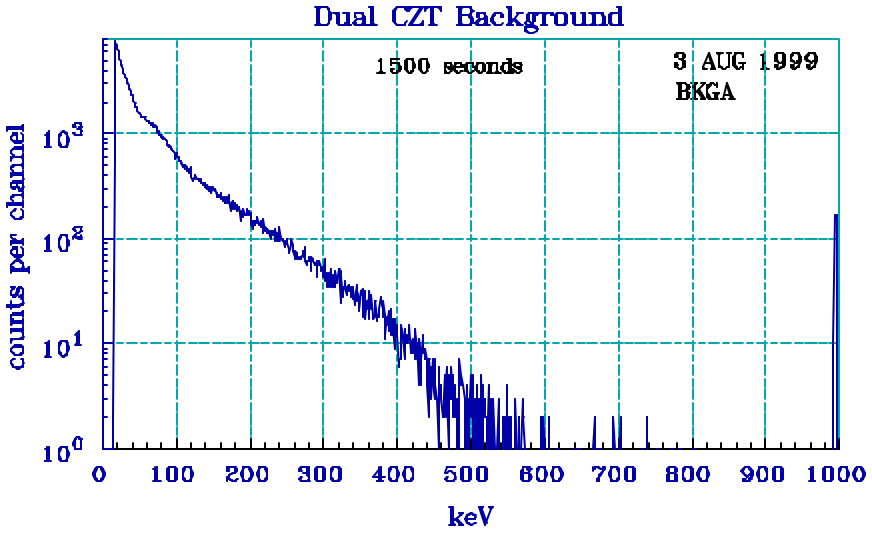


Figure 7. CZT background, dual crystal array.

The background used for the MDA analysis, presented in a following section, uses a line fitted to the FW50M data derived from integration over specific peak regions. This is given by:

$$3\sigma \text{ background } = 52.033 \times \sqrt{(\#\text{ of detectors} / 2)} \times \text{keV}^{-0.7782}$$

In this equation, the number of detectors is entered as an explicit parameter as a convenient way to allow expansion of the process to larger detector numbers, 256 and 1024 for example. The keV value required is that of the peak in question.

Efficiency

This paper uses intrinsic efficiency as one of the parameters in the MDA calculation. Intrinsic efficiency has units of (counts/incident gamma) and thus is a measure of the detector material characteristics. It is a useful way to insure that the detector assembly and associated electronics are performing satisfactorily when many different construction techniques are used. Figure 8, presents data from an early dual crystal array taken with a variety of medical, industrial, and special nuclear material (SNM) sources. The shape of the curve below approximately 80 keV is not modeled, and, for the few isotopic peaks in this region, the actual measured efficiency data are used.

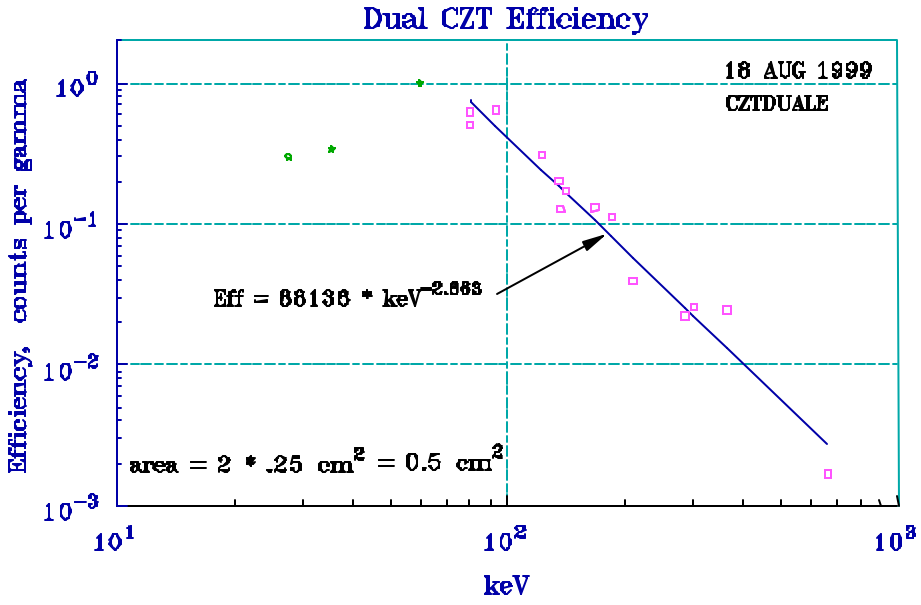


Figure 8. Intrinsic efficiency for a dual crystal array.

These data were taken under carefully controlled laboratory conditions using NIM BIN electronics. Subsequent data were taken with a variety of battery operated instruments, some using the 8-crystal array design. A comparison is shown in Figure 9.

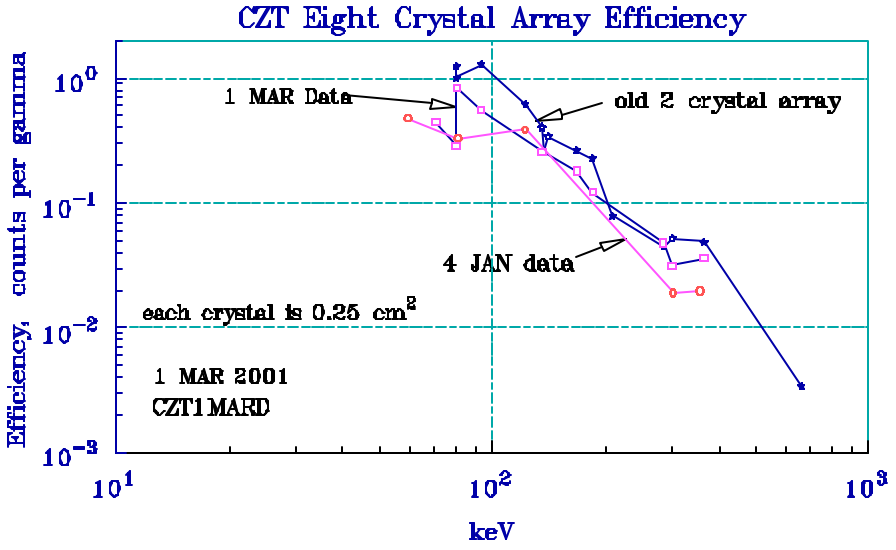


Figure 9. Intrinsic efficiency comparison.

The scatter in the data reflect differences in instrument response, source types available at the different times, and variations in source positioning methods (i.e., source to crystal distances). The data in Figure 8 have been used in the MDA calculations since this set had the source positions arranged more accurately.

MINIMUM DETECTABLE ACTIVITY (MDA)

The MDA is an isotopic specific parameter that readily allows comparisons between detector systems. The MDA in this paper uses a 3σ criterion, i.e., a peak is said to be 'detected' if its net area is at least three times the standard deviation of the system background in the peak region. The peak region is chosen to be FW50M, the width of the peak at 1/50 the peak height. There are many other MDA criteria that can be used. The one chosen here is fairly simple to calculate given the proper set of measured data.

The MDA uses values for the background counting rate at FW50M, the detection efficiency, the detector area facing the source, the source to detector distance, and the counting time together with source parameters such as gamma energy, gamma yield, and Ci/gram to provide an estimate of the MDA for each source gamma line examined. The preceding sections have presented data for the detector parameters required. In these cases an equation fitting the measured parameters has been used to provide a way to enter the data into the MDA calculation.

There are many possible comparisons that can illustrate the place of CZT when used to detect and identify gamma sources. Table 1 presents one such comparison.

Table 1. MDA comparison.

Detector Type	^{235}U Source, 100 seconds counting time, 185 keV peak		
	MDA @ 20 cm	MDA @ 3 m	MDA @ 50 ft
2 x 2 NaI	0.63 g	14.1g	
8 crystal CZT array	3.3 g	74.0 g	
20 detector JT-cooled HPGe array		0.68 g	17.0 g *

* 1 knot pass

Note that these data were derived from measured data from a thin unshielded uranium source. The uranium was < 2-mm thick.

Also note that 74 grams of uranium, 2-mm thick, is a piece about 1.5 cm square.

Table 1 presents typical MDA values calculated as noted above with the counting time, distance, isotope and its gamma line specified. There are, of course, some additional considerations. The most important are: the NaI scintillator can be expected to exhibit this MDA only if other sources are not present (and background is reasonable), and the Joule Thomson (JT)-cooled HPGe system is very large compared to the other two detectors.

Another way the MDA calculations can be used is a comparison between the number of CZT crystals in an array and the expected MDA. Table 2 presents a limited number of these comparisons.

The MDA does not decrease linearly with an increase in the number of crystals because of the increase in background with detector area.

Table 2. MDA comparison *versus* number of crystals.

CZT MDA @ 5 m, 100 seconds counting time		
Number of Crystals	^{235}U, 185 keV peak	^{239}Pu, 375 keV peak
8	43 g	187 g
256	7 g	33 g
1024	3.89 g	16.5 g

There will be a trade-off in complexity and weight as the number of crystals is increased. We expect that the larger arrays will be made by combining several 8-crystal arrays with a limited number of ADCs. This would make field servicing easy since a failed array could be replaced as a unit. This concept and estimates of array weight and physical size are addressed in a subsequent section (see Hardware Design).

Another way that MDA calculations can be used for system planning is shown in Table 3 where distance is taken as one of the tabulated parameters. Here it is easy to see the effect of array size on detection at different distances for a limited counting time. In a practical application the counting time for a 100 m distance would be larger than 100 seconds. The MDA will vary as the square root of the counting time ratio.

Table 3. MDA comparison *versus* distance.

^{235}U MDA with CZT Arrays of Different Sizes		
Number of Crystals	Distance	MDA, grams, for a 100 second counting time
8	20 cm	0.07
8	5 m	43
8	100 m	42000
1024	20 cm	0.006
1024	5 m	3.8
1024	100 m	7400

The data in the preceding three tables were taken from more extensive MDA calculations presented below. These calculations include a large number of medical isotopes that are commonly encountered either in commerce or as part of a medical procedure. In addition several industrial isotopes as well as some SNM isotopes are included. The current versions of the portable instruments also include ^{233}U and ^{237}Np in their isotope identification routines. These MDA calculations are part of an Excel spreadsheet and may be extended to different distances, counting times, and array sizes with little effort. Each of these isotopes has also been placed in the isotope identification program in several hand portable instruments and actual identification verified. In some cases shielding was added as well as a second isotope and the identification correctly accomplished.

CZT8DETMDA.xls			8 CRYSTAL CZT IDD ARRAY AT 20 CM 14 JUL 2000						
Isotope	keV	yield	Efficiency, counts per gamma	3 Sigma Bkg, cps	at 20 cm, 1 sec MDA, Ci	Specific Activity, Ci/g	at 20 cm, 1 sec MDA,grams	at 20 cm, 100 sec MDA, grams	at 20 cm, 100 sec MDA, Ci
U-235	143.786	0.105	0.1582	1.0893	4.45E-06	2.16E-06	2.06E+00	2.06E-01	
	163.379	0.047	0.1126	0.9862	1.27E-05	2.16E-06	5.85E+00	5.85E-01	
	185.739	0.53	0.0800	0.8925	1.43E-06	2.16E-06	6.61E-01	6.61E-02	
	205.333	0.047	0.0612	0.8255	1.95E-05	2.16E-06	9.01E+00	9.01E-01	
Pu-239	203.52	0.0000056	0.0627	0.8312	1.61E-01	0.062	2.59E+00	2.59E-01	
	344.94	0.0000057	0.0154	0.5513	4.27E-01	0.062	6.89E+00	6.89E-01	
	375.018	0.0000158	0.0123	0.5166	1.80E-01	0.062	2.91E+00	2.91E-01	
	413.691	0.0000151	0.0095	0.4786	2.27E-01	0.062	3.66E+00	3.66E-01	
U-238	295.22	0.189	0.0233	0.6223	9.60E-06	3.35E-07	2.87E+01	2.87E+00	
	351.99	0.363	0.0146	0.5427	6.97E-06	3.35E-07	2.08E+01	2.08E+00	
	609.37	0.428	0.0034	0.3541	1.66E-05	3.35E-07	4.96E+01	4.96E+00	
In-111	171.28	0.9093	0.0993	0.9506	7.15E-07				7.15E-08
	245.39	0.94	0.0381	0.7186	1.36E-06				1.36E-07
Tl-201	80.3	0.208	0.7463	1.7141	7.50E-07				7.50E-08
	135.34	0.028	0.1859	1.1418	1.49E-05				1.49E-06
	167.43	0.106	0.1055	0.9676	5.88E-06				5.88E-07
Ga-67	93.31	0.379	0.5003	1.5250	5.46E-07				5.46E-08
	184.58	0.209	0.0813	0.8969	3.58E-06				3.58E-07
	208.95	0.0237	0.0585	0.8144	3.99E-05				3.99E-06
	300.22	0.168	0.0223	0.6142	1.12E-05				1.12E-06
Xe-133	30.75	0.379	0.4018	3.6177	1.61E-06				1.61E-07
	81	0.371	0.7292	1.7025	4.27E-07				4.27E-08
I-131	80.18	0.0262	0.7492	1.7161	5.94E-06				5.94E-07
	284.3	0.0606	0.0257	0.6408	2.79E-05				2.79E-06
	364.48	0.812	0.0133	0.5282	3.33E-06				3.33E-07
I-125	27.5	1.395	0.3005	3.9463	6.39E-07				6.39E-08
	35.49	0.0667	0.3452	3.2358	9.55E-06				9.55E-07
Tc-99m	140.511	0.8897	0.1682	1.1090	5.03E-07				5.03E-08
Am-241	59.537	0.359	1.0130	2.1634	4.04E-07				4.04E-08
Co-57	122.06	0.856	0.2447	1.2374	4.01E-07				4.01E-08
	136.47	0.1058	0.1818	1.1345	4.01E-06				4.01E-07
Cs-137	661.66	0.851	0.0027	0.3321	9.76E-06				9.76E-07
Ba-133	80.997	0.232	0.7293	1.7026	6.84E-07				6.84E-08
	276.4	0.0717	0.0278	0.6550	2.24E-05				2.24E-06
	302.85	0.1832	0.0218	0.6101	1.04E-05				1.04E-06
	356.02	0.621	0.0141	0.5379	4.16E-06				4.16E-07
	383.85	0.0894	0.0116	0.5073	3.33E-05				3.33E-06

Efficiency = 88136 * keV^ -2.663 c/gamma >80 keV

3 sigma bkg = 52.033*keV^-0.7782 for the IDD 8 detector array

MDA at 20 cm in Ci = [3 sigma bkg / sqrt (integration time)] * 4 * pi() * 20^2 / (Efficiency * detector area* 3.7 E10 * yield)

MDA at 20 cm in grams = MDA at 20 cm in Ci / Ci per gram

CZT8DETMDA5m.xls			8 CRYSTAL CZT IDD ARRAY at 5 METERS 14 JUL 2000							
Isotope	keV	yield	Efficiency, counts per gamma	5 m 3 Sigma Bkg, cps	Air Absorption for 5 m	at 5 m , 1 sec MDA, Ci	Specific Activity, Ci/g	at 5 m, 1 sec MDA,grams	at 5 m, 100 sec MDA, grams	at 5 m, 100 sec MDA, Ci
U-235	143.786	0.105	0.1582	1.0541	0.9160	2.94E-03	2.16E-06	1.36E+03	1.36E+02	
	163.379	0.047	0.1126	0.9544	0.9199	8.33E-03	2.16E-06	3.85E+03	3.85E+02	
	185.739	0.53	0.0800	0.8637	0.9236	9.36E-04	2.16E-06	4.33E+02	4.33E+01	
	205.333	0.047	0.0612	0.7989	0.9263	1.27E-02	2.16E-06	5.88E+03	5.88E+02	
Pu-239	203.52	0.0000056	0.0627	0.8044	0.9261	1.05E+02	0.062	1.69E+03	1.69E+02	
	344.94	0.0000057	0.0154	0.5335	0.9392	2.75E+02	0.062	4.44E+03	4.44E+02	
	375.018	0.0000158	0.0123	0.4999	0.9410	1.16E+02	0.062	1.87E+03	1.87E+02	
	413.691	0.0000151	0.0095	0.4632	0.9431	1.46E+02	0.062	2.35E+03	2.35E+02	
U-238	295.22	0.189	0.0233	0.6022	0.9355	6.21E-03	3.35E-07	1.85E+04	1.85E+03	
	351.99	0.363	0.0146	0.5252	0.9396	4.48E-03	3.35E-07	1.34E+04	1.34E+03	
	609.37	0.428	0.0034	0.3426	0.9507	1.06E-02	3.35E-07	3.16E+04	3.16E+03	
In-111	171.28	0.9093	0.0993	0.9199	0.9212	4.70E-04				4.70E-05
	245.39	0.94	0.0381	0.6954	0.9310	8.85E-04				8.85E-05
Tl-201	80.3	0.208	0.7463	1.6587	0.8962	5.06E-04				5.06E-05
	135.34	0.028	0.1859	1.1050	0.9142	9.86E-03				9.86E-04
	167.43	0.106	0.1055	0.9364	0.9206	3.86E-03				
Ga-67	93.31	0.379	0.5003	1.4758	0.9017	3.66E-04				3.66E-05
	184.58	0.209	0.0813	0.8679	0.9234	2.35E-03				2.35E-04
	208.95	0.0237	0.0585	0.7881	0.9268	2.61E-02				2.61E-03
	300.22	0.168	0.0223	0.5944	0.9359	7.21E-03				7.21E-04
Xe-133	30.75	0.379	0.4018	3.5010	0.8538	1.14E-03				1.14E-04
	81	0.371	0.7292	1.6476	0.8966	2.88E-04				2.88E-05
I-131	80.18	0.0262	0.7492	1.6607	0.8962	4.01E-03				4.01E-04
	284.3	0.0606	0.0257	0.6202	0.9346	1.81E-02				1.81E-03
	364.48	0.812	0.0133	0.5111	0.9404	2.14E-03				2.14E-04
I-125	27.5	1.395	0.3005	3.8189	0.8479	4.56E-04				4.56E-05
	35.49	0.0667	0.3452	3.1314	0.8610	6.71E-03				6.71E-04
Tc-99m	140.511	0.8897	0.1682	1.0732	0.9153	3.33E-04				3.33E-05
Am-241	59.537	0.359	1.0130	2.0936	0.8844	2.76E-04				2.76E-05
Co-57	122.06	0.856	0.2447	1.1975	0.9109	2.66E-04				2.66E-05
	136.47	0.1058	0.1818	1.0979	0.9144	2.65E-03				2.65E-04
Cs-137	661.66	0.851	0.0027	0.3214	0.9522	6.20E-03				6.20E-04
Ba-133	80.997	0.232	0.7293	1.6476	0.8966	4.61E-04				4.61E-05
	276.4	0.0717	0.0278	0.6339	0.9340	1.45E-02				1.45E-03
	302.85	0.1832	0.0218	0.5904	0.9362	6.72E-03				6.72E-04
	356.02	0.621	0.0141	0.5206	0.9399	2.68E-03				2.68E-04
	383.85	0.0894	0.0116	0.4909	0.9415	2.14E-02				2.14E-03
Efficiency = 88136 * keV^ -2.663 c/gamma >80 keV										
3 sigma bkg = 52.033*keV^-0.7782 for the 8 detector array at zero feet										
bkg at 5 m = bkg at zero feet*EXP(-0.0020*5*39.37/12)										
MU = 0.905*keV^-0.382 air attenuation = EXP(-MU*500*0.001293) for 5 m										
MDA at 5 m in Ci = ([3 sigma bkg / sqrt (integration time)] * 4 * pi() * 500^2 / (Efficiency * detector area* 3.7 E10 * yield))/[air attenuation]										
MDA at 5 m in grams = MDA at 5 m in Ci / Ci per gram										

256 CRYSTAL CZT IDD ARRAY at 5 METERS 14 JUL 2000

Isotope	keV	yield	Efficiency, counts per gamma	5 m 3 Sigma Bkg, cps	Air Absorption for 5 m	at 5 m , 1 sec MDA, Ci	Specific Activity, Ci/g	at 5 m, 1 sec MDA,grams	at 5 m, 100 sec MDA, grams	at 5 m, 100 sec MDA, Ci
U-235	143.786	0.105	0.1582	5.9631	0.9160	5.20E-04	2.16E-06	2.40E+02	2.40E+01	
	163.379	0.047	0.1126	5.3988	0.9199	1.47E-03	2.16E-06	6.80E+02	6.80E+01	
	185.739	0.53	0.0800	4.8859	0.9236	1.66E-04	2.16E-06	7.65E+01	7.65E+00	
	205.333	0.047	0.0612	4.5191	0.9263	2.25E-03	2.16E-06	1.04E+03	1.04E+02	
Pu-239	203.52	0.0000056	0.0627	4.5504	0.9261	1.86E+01	0.062	2.99E+02	2.99E+01	
	344.94	0.0000057	0.0154	3.0181	0.9392	4.86E+01	0.062	7.84E+02	7.84E+01	
	375.018	0.0000158	0.0123	2.8280	0.9410	2.05E+01	0.062	3.30E+02	3.30E+01	
	413.691	0.0000151	0.0095	2.6200	0.9431	2.57E+01	0.062	4.15E+02	4.15E+01	
U-238	295.22	0.189	0.0233	3.4067	0.9355	1.10E-03	3.35E-07	3.28E+03	3.28E+02	
	351.99	0.363	0.0146	2.9710	0.9396	7.93E-04	3.35E-07	2.37E+03	2.37E+02	
	609.37	0.428	0.0034	1.9383	0.9507	1.87E-03	3.35E-07	5.58E+03	5.58E+02	
In-111	171.28	0.9093	0.0993	5.2040	0.9212	8.30E-05				8.30E-06
	245.39	0.94	0.0381	3.9339	0.9310	1.57E-04				1.57E-05
Tl-201	80.3	0.208	0.7463	9.3833	0.8962	8.95E-05				8.95E-06
	135.34	0.028	0.1859	6.2507	0.9142	1.74E-03				1.74E-04
	167.43	0.106	0.1055	5.2969	0.9206	6.83E-04				
Ga-67	93.31	0.379	0.5003	8.3485	0.9017	6.48E-05				6.48E-06
	184.58	0.209	0.0813	4.9098	0.9234	4.15E-04				4.15E-05
	208.95	0.0237	0.0585	4.4581	0.9268	4.61E-03				4.61E-04
	300.22	0.168	0.0223	3.3625	0.9359	1.27E-03				1.27E-04
Xe-133	30.75	0.379	0.4018	19.8045	0.8538	2.02E-04				2.02E-05
	81	0.371	0.7292	9.3201	0.8966	5.10E-05				5.10E-06
I-131	80.18	0.0262	0.7492	9.3942	0.8962	7.08E-04				7.08E-05
	284.3	0.0606	0.0257	3.5081	0.9346	3.19E-03				3.19E-04
	364.48	0.812	0.0133	2.8914	0.9404	3.78E-04				3.78E-05
I-125	27.5	1.395	0.3005	21.6031	0.8479	8.06E-05				8.06E-06
	35.49	0.0667	0.3452	17.7138	0.8610	1.19E-03				1.19E-04
Tc-99m	140.511	0.8897	0.1682	6.0710	0.9153	5.88E-05				5.88E-06
Am-241	59.537	0.359	1.0130	11.8431	0.8844	4.89E-05				4.89E-06
Co-57	122.06	0.856	0.2447	6.7738	0.9109	4.71E-05				4.71E-06
	136.47	0.1058	0.1818	6.2104	0.9144	4.68E-04				4.68E-05
Cs-137	661.66	0.851	0.0027	1.8180	0.9522	1.10E-03				1.10E-04
Ba-133	80.997	0.232	0.7293	9.3204	0.8966	8.15E-05				8.15E-06
	276.4	0.0717	0.0278	3.5859	0.9340	2.56E-03				2.56E-04
	302.85	0.1832	0.0218	3.3398	0.9362	1.19E-03				1.19E-04
	356.02	0.621	0.0141	2.9447	0.9399	4.73E-04				4.73E-05
	383.85	0.0894	0.0116	2.7772	0.9415	3.78E-03				3.78E-04

Efficiency = 88136 * keV^ -2.663 c/gamma >80 keV

3 sigma bkg = 52.033*SQRT(# of detectors/8)*keV^-0.7782 for the IDD array at zero feet

bkg at 5 m = (bkg at zero feet*EXP(-0.0020*5*39.37/12)

MU = 0.905*keV^-0.382 air attenuation = EXP(-MU*500*0.001293) for 5 m

MDA at 5 m in Ci = ([3 sigma bkg / sqrt (integration time)] * 4 * pi() * 500^2 / (Efficiency * detector area* 3.7 E10 * yield))/[air attenuation]

MDA at 5 m in grams = MDA at 5 m in Ci / Ci per gram

1024 CRYSTAL CZT IDD ARRAY at 20 cm 14 JUL 2000

Isotope	keV	yield	Efficiency, counts per gamma	20 cm 3 Sigma Bkg, cps	Air Absorption for 20 cm	at 20 cm , 1 sec MDA, Ci	Specific Activity, Ci/g	at 20 cm, 1 sec MDA,grams	at 20 cm, 100 sec MDA, grams	at 100 m, 100 sec MDA, Ci
U-235	143.786	0.105	0.1582	12.3239	0.9965	3.95E-07	2.16E-06	1.83E-01	1.83E-02	
	163.379	0.047	0.1126	11.1577	0.9967	1.12E-06	2.16E-06	5.19E-01	5.19E-02	
	185.739	0.53	0.0800	10.0977	0.9968	1.27E-07	2.16E-06	5.86E-02	5.86E-03	
	205.333	0.047	0.0612	9.3396	0.9969	1.73E-06	2.16E-06	7.98E-01	7.98E-02	
Pu-239	203.52	0.0000056	0.0627	9.4043	0.9969	1.43E-02	0.062	2.30E-01	2.30E-02	
	344.94	0.0000057	0.0154	6.2375	0.9975	3.78E-02	0.062	6.10E-01	6.10E-02	
	375.018	0.0000158	0.0123	5.8446	0.9976	1.60E-02	0.062	2.58E-01	2.58E-02	
	413.691	0.0000151	0.0095	5.4149	0.9977	2.01E-02	0.062	3.24E-01	3.24E-02	
U-238	295.22	0.189	0.0233	7.0407	0.9973	8.51E-07	3.35E-07	2.54E+00	2.54E-01	
	351.99	0.363	0.0146	6.1401	0.9975	6.17E-07	3.35E-07	1.84E+00	1.84E-01	
	609.37	0.428	0.0034	4.0058	0.9980	1.47E-06	3.35E-07	4.39E+00	4.39E-01	
In-111	171.28	0.9093	0.0993	10.7551	0.9967	6.34E-08				6.34E-09
	245.39	0.94	0.0381	8.1301	0.9971	1.21E-07				1.21E-08
Tl-201	80.3	0.208	0.7463	19.3925	0.9956	6.66E-08				6.66E-09
	135.34	0.028	0.1859	12.9184	0.9964	1.32E-06				1.32E-07
	167.43	0.106	0.1055	10.9470	0.9967	5.21E-07				5.21E-08
Ga-67	93.31	0.379	0.5003	17.2538	0.9959	4.85E-08				4.85E-09
	184.58	0.209	0.0813	10.1470	0.9968	3.18E-07				3.18E-08
	208.95	0.0237	0.0585	9.2135	0.9970	3.54E-06				3.54E-07
	300.22	0.168	0.0223	6.9493	0.9974	9.88E-07				9.88E-08
Xe-133	30.75	0.379	0.4018	40.9301	0.9937	1.44E-07				1.44E-08
	81	0.371	0.7292	19.2620	0.9956	3.79E-08				3.79E-09
I-131	80.18	0.0262	0.7492	19.4151	0.9956	5.27E-07				5.27E-08
	284.3	0.0606	0.0257	7.2503	0.9973	2.47E-06				2.47E-07
	364.48	0.812	0.0133	5.9757	0.9975	2.95E-07				2.95E-08
I-125	27.5	1.395	0.3005	44.6473	0.9934	5.69E-08				5.69E-09
	35.49	0.0667	0.3452	36.6093	0.9940	8.49E-07				8.49E-08
Tc-99m	140.511	0.8897	0.1682	12.5469	0.9965	4.47E-08				4.47E-09
Am-241	59.537	0.359	1.0130	24.4762	0.9951	3.59E-08				3.59E-09
Co-57	122.06	0.856	0.2447	13.9995	0.9963	3.56E-08				3.56E-09
	136.47	0.1058	0.1818	12.8351	0.9964	3.55E-07				3.55E-08
Cs-137	661.66	0.851	0.0027	3.7572	0.9980	8.65E-07				8.65E-08
Ba-133	80.997	0.232	0.7293	19.2625	0.9956	6.07E-08				6.07E-09
	276.4	0.0717	0.0278	7.4110	0.9973	1.98E-06				1.98E-07
	302.85	0.1832	0.0218	6.9023	0.9974	9.21E-07				9.21E-08
	356.02	0.621	0.0141	6.0859	0.9975	3.69E-07				3.69E-08
	383.85	0.0894	0.0116	5.7397	0.9976	2.95E-06				2.95E-07

Efficiency = 88136 * keV^ -2.663 c/gamma >80 keV

3 sigma bkg = 52.033*SQRT(# of crystals/8)*keV^-0.7782

bkg at 5 m = (3 sigma bkg at zero feet) * EXP (-0.0020*5*39.37/12)

MU = 0.905*keV^-0.382 air attenuation = EXP(-MU*10000*0.001293)

MDA at 20 cm in Ci = ([3 sigma bkg / sqrt (integration time)] * 4 * pi() * 20^2 / (Efficiency * detector area* 3.7 E10 * yield))/[air attenuation]

MDA at 20 cm in grams = MDA at 20 cm in Ci / Ci per gram

1024 CRYSTAL CZT IDD ARRAY at 5 METERS 14 JUL 2000

Isotope	keV	yield	Efficiency, counts per gamma	5 m 3 Sigma Bkg, cps	Air Absorption for 5 m	at 5 m , 1 sec MDA, Ci	Specific Activity, Ci/g	at 5 m, 1 sec MDA,grams	at 5 m, 100 sec MDA, grams	at 5 m, 100 sec MDA, Ci
U-235	143.786	0.105	0.1582	11.9262	0.9160	2.60E-04	2.16E-06	1.20E+02	1.20E+01	
	163.379	0.047	0.1126	10.7976	0.9199	7.36E-04	2.16E-06	3.40E+02	3.40E+01	
	185.739	0.53	0.0800	9.7718	0.9236	8.28E-05	2.16E-06	3.83E+01	3.83E+00	
	205.333	0.047	0.0612	9.0382	0.9263	1.12E-03	2.16E-06	5.20E+02	5.20E+01	
Pu-239	203.52	0.0000056	0.0627	9.1008	0.9261	9.28E+00	0.062	1.50E+02	1.50E+01	
	344.94	0.0000057	0.0154	6.0362	0.9392	2.43E+01	0.062	3.92E+02	3.92E+01	
	375.018	0.0000158	0.0123	5.6560	0.9410	1.02E+01	0.062	1.65E+02	1.65E+01	
	413.691	0.0000151	0.0095	5.2401	0.9431	1.29E+01	0.062	2.08E+02	2.08E+01	
U-238	295.22	0.189	0.0233	6.8135	0.9355	5.49E-04	3.35E-07	1.64E+03	1.64E+02	
	351.99	0.363	0.0146	5.9419	0.9396	3.96E-04	3.35E-07	1.18E+03	1.18E+02	
	609.37	0.428	0.0034	3.8765	0.9507	9.35E-04	3.35E-07	2.79E+03	2.79E+02	
In-111	171.28	0.9093	0.0993	10.4079	0.9212	4.15E-05				4.15E-06
	245.39	0.94	0.0381	7.8677	0.9310	7.83E-05				7.83E-06
Tl-201	80.3	0.208	0.7463	18.7666	0.8962	4.47E-05				4.47E-06
	135.34	0.028	0.1859	12.5014	0.9142	8.72E-04				8.72E-05
	167.43	0.106	0.1055	10.5937	0.9206	3.41E-04				
Ga-67	93.31	0.379	0.5003	16.6970	0.9017	3.24E-05				3.24E-06
	184.58	0.209	0.0813	9.8195	0.9234	2.07E-04				2.07E-05
	208.95	0.0237	0.0585	8.9162	0.9268	2.30E-03				2.30E-04
	300.22	0.168	0.0223	6.7250	0.9359	6.37E-04				6.37E-05
Xe-133	30.75	0.379	0.4018	39.6090	0.8538	1.01E-04				1.01E-05
	81	0.371	0.7292	18.6403	0.8966	2.55E-05				2.55E-06
I-131	80.18	0.0262	0.7492	18.7885	0.8962	3.54E-04				3.54E-05
	284.3	0.0606	0.0257	7.0163	0.9346	1.60E-03				1.60E-04
	364.48	0.812	0.0133	5.7828	0.9404	1.89E-04				1.89E-05
I-125	27.5	1.395	0.3005	43.2063	0.8479	4.03E-05				4.03E-06
	35.49	0.0667	0.3452	35.4277	0.8610	5.93E-04				5.93E-05
Tc-99m	140.511	0.8897	0.1682	12.1419	0.9153	2.94E-05				2.94E-06
Am-241	59.537	0.359	1.0130	23.6862	0.8844	2.44E-05				2.44E-06
Co-57	122.06	0.856	0.2447	13.5477	0.9109	2.36E-05				2.36E-06
	136.47	0.1058	0.1818	12.4208	0.9144	2.34E-04				2.34E-05
Cs-137	661.66	0.851	0.0027	3.6359	0.9522	5.48E-04				5.48E-05
Ba-133	80.997	0.232	0.7293	18.6408	0.8966	4.08E-05				4.08E-06
	276.4	0.0717	0.0278	7.1718	0.9340	1.28E-03				1.28E-04
	302.85	0.1832	0.0218	6.6795	0.9362	5.94E-04				5.94E-05
	356.02	0.621	0.0141	5.8895	0.9399	2.37E-04				2.37E-05
	383.85	0.0894	0.0116	5.5544	0.9415	1.89E-03				1.89E-04

Efficiency = 88136 * keV^ -2.663 c/gamma >80 keV

3 sigma bkg = 52.033*SQRT(# of detectors/8)*keV^-0.7782 for the array at zero feet

bkg at 5 m = (bkg at zero feet*EXP(-0.0020*5*39.37/12)

MU = 0.905*keV^-0.382 air attenuation = EXP(-MU*500*0.001293) for 5 m

MDA at 5 m in Ci = ([3 sigma bkg / sqrt (integration time)] * 4 * pi() * 500^2 / (Efficiency * detector area* 3.7 E10 * yield))/[air attenuation]

MDA at 5 m in grams = MDA at 5 m in Ci / Ci per gram

1024 CRYSTAL CZT IDD ARRAY at 100 METERS 14 JUL 2000

Isotope	keV	yield	Efficiency, counts per gamma	100 m 3 Sigma Bkg, cps	Air Absorption for 100 m	at 100 m , 1 sec MDA, Ci	Specific Activity, Ci/g	at 100 m, 1 sec MDA,grams	at 100 m, 100 sec MDA, grams	at 100 m, 100 sec MDA, Ci
U-235	143.786	0.105	0.1582	6.3941	0.1731	2.95E-01	2.16E-06	1.36E+05	1.36E+04	
	163.379	0.047	0.1126	5.7890	0.1882	7.71E-01	2.16E-06	3.57E+05	3.57E+04	
	185.739	0.53	0.0800	5.2391	0.2038	8.04E-02	2.16E-06	3.72E+04	3.72E+03	
	205.333	0.047	0.0612	4.8457	0.2164	1.03E+00	2.16E-06	4.77E+05	4.77E+04	
Pu-239	203.52	0.0000056	0.0627	4.8793	0.2153	8.56E+03	0.062	1.38E+05	1.38E+04	
	344.94	0.0000057	0.0154	3.2363	0.2849	1.72E+04	0.062	2.77E+05	2.77E+04	
	375.018	0.0000158	0.0123	3.0324	0.2964	6.98E+03	0.062	1.13E+05	1.13E+04	
	413.691	0.0000151	0.0095	2.8094	0.3100	8.40E+03	0.062	1.35E+05	1.35E+04	
U-238	295.22	0.189	0.0233	3.6530	0.2638	4.17E-01	3.35E-07	1.25E+06	1.25E+05	
	351.99	0.363	0.0146	3.1857	0.2877	2.78E-01	3.35E-07	8.29E+05	8.29E+04	
	609.37	0.428	0.0034	2.0784	0.3641	5.23E-01	3.35E-07	1.56E+06	1.56E+05	
In-111	171.28	0.9093	0.0993	5.5801	0.1939	4.23E-02				4.23E-03
	245.39	0.94	0.0381	4.2182	0.2393	6.53E-02				6.53E-03
Tl-201	80.3	0.208	0.7463	10.0615	0.1118	7.69E-02				7.69E-03
	135.34	0.028	0.1859	6.7025	0.1661	1.03E+00				1.03E-01
	167.43	0.106	0.1055	5.6797	0.1911	3.53E-01				3.53E-02
Ga-67	93.31	0.379	0.5003	8.9519	0.1263	4.96E-02				4.96E-03
	184.58	0.209	0.0813	5.2646	0.2031	2.02E-01				2.02E-02
	208.95	0.0237	0.0585	4.7803	0.2186	2.09E+00				2.09E-01
	300.22	0.168	0.0223	3.6055	0.2661	4.80E-01				4.80E-02
Xe-133	30.75	0.379	0.4018	21.2360	0.0424	4.37E-01				4.37E-02
	81	0.371	0.7292	9.9938	0.1126	4.35E-02				4.35E-03
I-131	80.18	0.0262	0.7492	10.0733	0.1117	6.10E-01				6.10E-02
	284.3	0.0606	0.0257	3.7617	0.2588	1.24E+00				1.24E-01
	364.48	0.812	0.0133	3.1004	0.2925	1.30E-01				1.30E-02
I-125	27.5	1.395	0.3005	23.1646	0.0369	1.99E-01				1.99E-02
	35.49	0.0667	0.3452	18.9942	0.0501	2.18E+00				2.18E-01
Tc-99m	140.511	0.8897	0.1682	6.5098	0.1704	3.39E-02				3.39E-03
Am-241	59.537	0.359	1.0130	12.6992	0.0858	5.40E-02				5.40E-03
Co-57	122.06	0.856	0.2447	7.2634	0.1546	2.98E-02				2.98E-03
	136.47	0.1058	0.1818	6.6593	0.1671	2.75E-01				2.75E-02
Cs-137	661.66	0.851	0.0027	1.9494	0.3757	2.98E-01				2.98E-02
Ba-133	80.997	0.232	0.7293	9.9941	0.1126	6.96E-02				6.96E-03
	276.4	0.0717	0.0278	3.8451	0.2550	1.01E+00				1.01E-01
	302.85	0.1832	0.0218	3.5812	0.2673	4.46E-01				4.46E-02
	356.02	0.621	0.0141	3.1576	0.2893	1.65E-01				1.65E-02
	383.85	0.0894	0.0116	2.9780	0.2996	1.27E+00				1.27E-01

Efficiency = 88136 * keV^ -2.663 c/gamma >80 keV

3 sigma bkg = 52.033*SQRT(# of crystals/8)*keV^-0.7782 for the 1024 detector IDD array at zero feet

bkg at 100 m = (bkg at zero feet*EXP(-0.0020*100*39.37/12)

MU = 0.905*keV^-0.382 air attenuation = EXP(-MU*10000*0.001293)

MDA at 100 m in Ci = ([3 sigma bkg / sqrt (integration time)] * 4 * pi() * 10000^2 / (Efficiency * detector area* 3.7 E10 * yield))/[air attenuation]

MDA at 100 m in grams = MDA at 100 m in Ci / Ci per gram

The MDA values for a new time and distance can be readily derived from the tabulated data given above. These new MDA values are inversely related to the counting time and directly related to the square of the new distance. Figure 10, below, shows one simple way that this relationship can be visualized.

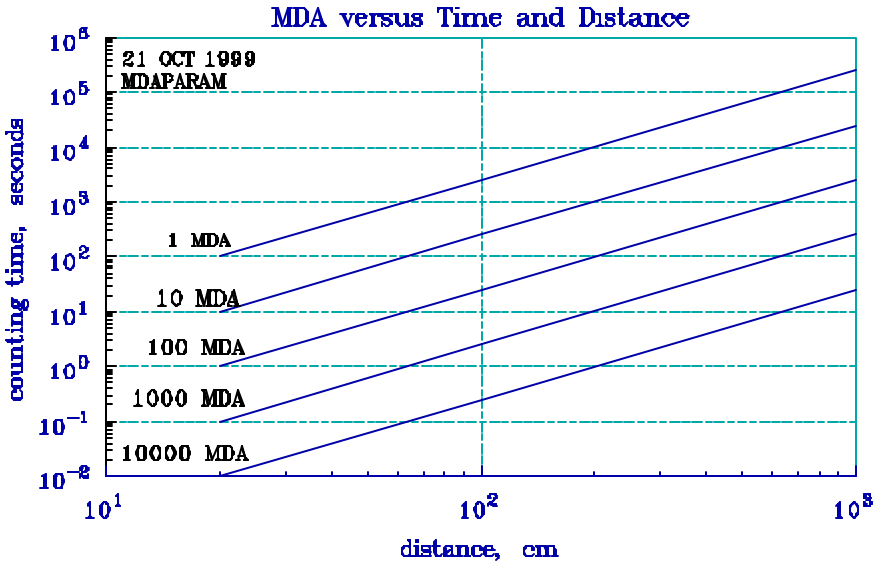


Figure 10. MDA parameters *versus* time and distance based upon 8 crystals and 20 cm distance.

As an example, suppose we have 100 seconds to count and the distance is 200 cm rather than 20 cm. The MDA value in the figure for these parameters is 100, i.e., the actual MDA will be 100 times the tabulated value at 20 cm. If the sample was at 1000 cm and the counting time was 1000 seconds the MDA value would be about 250 times the 20 cm value.

HARDWARE DESIGN

The following sections describe current hardware designs, two of which have been fabricated, tested, and delivered to the sponsors. A 32-crystal array is briefly described and details of a very small instrument are discussed. Lastly, estimates are given for the weight of a large array suitable for aerial detection.

The first section describes the CZT detector module which is used in all the large instruments. This module, containing eight CZT crystals, is the basis for most of the preceding spectra and MDA tables. We expect that larger arrays will be constructed of multiple copies of the basic 8-crystal array.

Hardware Design - 8-Crystal Detector Module

The CZT detector module contains eight $5 \times 5 \times 5$ mm CZT crystals. These crystals are cubical and have a planar electrode on one face and a cap electrode on the opposite face. These crystals, all analog electronics, the HVPS, and a small heater (for very low temperature operation) are housed in an aluminum box approximately $2.25 \times 3 \times 0.75$ inches.

The CZT crystals are arranged in a 2×4 grid with adjacent centers 8 mm apart. PC board traces and flexible conductive spacers are used to couple to the CZT electrodes. Each pair of CZT crystals is connected to an field effect transistor (FET) preamplifier followed by a shaping amplifier. These are all surface mount parts. Each shaping amplifier has its own miniature output connector.

The HVPS is a Cockcroft-Walton design and is assembled on a second PC board that forms the other half of the detector module. Gold pads and conductive elastomeric pieces are used to connect to the CZT crystals. The HVPS operates at a high frequency, well outside the pass band of the linear amplifiers, and thus does not contribute to resolution degradation. The HVPS is regulated to 1% and stabilizes in 3 seconds at turn on. A second version of this power supply provides a tap for operation of the G-M tube. A third version of this power supply lets the high voltage drift down and then restarts the oscillator. This so-called pulsed operation cuts the high voltage power consumption by approximately 20% at the expense of a 3 to 5% increase in system noise. This shows up as resolution degradation.

Other characteristics of the CZT detector module are:

- Operates from ± 5 VDC at less than 0.5 mA
- Operating temperature range from -25 to +50ºC. The low temperature operation can be extended to -35 ºC with a simple resistive heater driven by a temperature sensor.
- Vibration resistant due to the elastomeric crystal mounting material. Modules are shock resistant as well, and survive 8 foot drops to concrete with only cosmetic damage to the case.
- Weights ~100 grams with connectors.

A low-power version has been constructed and tested using the pulsed HVPS. In this design all eight crystals are summed into one FET resulting in a 60% reduction in analog power consumption. The penalty paid is a factor of two decrease in resolution.

Hardware Design - Large Complex Portable Instrument

One application of the CZT array described above has been in a large portable instrument. This device was intended to provide a search means to find a 'hot' spot on a box, package, or person. Once the 'hot' spot was found the instrument used the CZT array to identify the isotope and display the data. In addition to these features, the instrument contained ^{3}He proportional counter tubes for neutron detection, and a means to estimate exposure rates from background up to 2 R/hr.

The salient characteristics of this instrument were:

- Isotope identification was the most important feature. Good energy resolution is important for correct isotope identification. There were 18 medical, SNM, and industrial isotopes in the library.
- The 8-CZT crystals were used in a 4×2 array with four ADCs, one for each crystal pair. The spectra were digitally summed after gain and offset corrections for each of the four crystal pairs. The conversion gain was 4096 channels. The instrument stored five spectra; one spectrum each for the 4-crystal pairs, and the summed spectrum. An RS-232 port was provided allowing download to a computer for additional analysis or display.
- The instrument had an LCD display that gave the user information about the isotopes found, the neutron rate, and exposure rate.
- There were LEDs that illuminated to alert the user that neutrons were present, that SNM had been detected, that the preset exposure rate had been reached, and that the batteries are weak. Two different audio indicators were also provided that indicated neutron rates and gamma rates separately.
- In addition to the CZT array, a 2×2 NaI crystal, HVPS and separate ADC were provided. The 2×2 was used to find 'hot' spots, and to identify ^{137}Cs and ^{60}Co. In addition, the 2×2 spectra were used to calculate exposure rates from background to 2 mR/hr. Energy corrections were applied to yield exposure rate data that were nearly tissue equivalent from 40 keV to 3 MeV.
- A small energy compensated G-M tube was also included to provide exposure rate data from 2 mR/hr to 2 R/hr.
- The instrument case was made out of plastic to provide moderator for the ^{3}He neutron detectors. The case interior was flame sprayed to enable the instrument to pass EMI tests from a 5 watt transceiver at 1 foot.
- The instrument operated on four NiCd batteries for six hours. It could be recharged in eight hours, and would operate while being charged.
- The overall case was $12 \times 7 \times 6$ inches including the large handle. The instrument weighed 9 lbs. 10 oz. Two instruments were fabricated.

Hardware Design -- Low Power Small Instrument

This device is a rugged instrument with isotope identification, exposure rate display, and a 'hot' spot location tool. It measures gammas only. The package developed has the following characteristics:

- The CZT 8-crystal module was used with all eight crystals summed into one preamplifier to save power. In addition, the pulsed HVPS was used, again to save power. There was only one ADC and the isotope library was restricted to 15 isotopes. These compromises resulted in an energy resolution that was approximately a factor of two worse than the larger instrument described above. This degradation was due to the added noise caused by the analog summing of all eight crystals into one preamplifier, and by the pulsed HVPS.
- The instrument displayed the isotope category as: SNM, Medical, or Other via LEDs. There was no LCD alpha numeric display.
- There was a locate mode with an LED array, an audio alarm, and a vibrator. The latter two were switchable. The locate mode used the gross counts from the CZT module.
- An energy compensated G-M tube was used to provide exposure rate data from approximately 10 μR/hr up to 10 R/hr via an LED array.
- The instrument stores six spectra with time and date stamping for later download through an RS-232 port. There is room in the memory for at least 20 more spectra.
- The instrument operates from two 2/3 A lithium batteries for >8 hours.
- The instrument case is $2.75 \times 4.75 \times 3.25$ inches and weighs 18 oz. including batteries. A rubber boot is provided covering the back and sides of the instrument. There are no protruding parts or switches.
- Three instruments were fabricated.

Smart Portal Array

An instrument is presently under construction that incorporates several changes based upon experience with the 8-crystal array in the preceding instruments.

The goal of this new construction is a large module with 32 crystals that will be part of a portal monitor capable of isotope identification in a few seconds. We expect that a full scale portal will use at least four of these 32-crystal modules. This should provide isotope detection covering both sides of a person.

The 32-crystal module is constructed from four of the 8-crystal modules described above with some modifications. Each crystal pair is summed into one preamplifier. The individual preamplifier outputs are multiplexed into one ADC. Upon digitization each pulse is gain and offset corrected before being stored in a common memory area. The lower noise Cockcroft-Walton HVPS is used (without the pulse capability) in each 8-crystal module. These

modifications will produce the best energy resolution that the CZT arrays can deliver. Since AC power will be used there is no need to try for the lowest power consumption.

At the present time one 32-crystal array has been fabricated. The isotope identification software will be adapted from the large instrument described previously.

Very Small Instrument Design

A paper study has been completed suggesting that a very small instrument could be designed and fabricated that would be the size of a fat pen or pencil. One or two CZT crystals would be used initially in the detector part of this instrument. This part could be 1.5 cm in diameter by 4-cm long. All the analog electronics and the crystals would be in this section.

The ADC, memory, and digital control would be in a similar sized section connected by a thin cable with the detector module. The HVPS, and the batteries would be in a third module, possibly 6 cm long. This module would be connected to the ADC/memory module with a thin coax cable.

The completed instrument would consist of these three modules inter-connected via a thin coax. The coax inter-connections could be made any reasonable length to assist in field placement.

The instrument would be able to collect time stamped spectra for later download and examination in the laboratory. No data processing, display, alarms, etc. would be present in the instrument. This would trim weight, power and minimize field setup time.

Large Array Suitable for Aerial Survey Work

This design consists of 1024 crystals made up of 128 8-crystal arrays. The expected MDA values for a 100 m altitude, for example, have been presented in a previous section. This large collection of electronic parts will weigh approximately 20 kg complete with the necessary ADCs and storage devices. A thin shadow shield is contemplated that will restrict the field of view to a cone immediately below the aircraft.

IDENTIFICATION SOFTWARE - OVERVIEW

The CZT crystal arrays are inefficient. In practical terms this limits the counts accumulated in a typical spectrum. The gamma peaks may be small and poorly shaped despite efforts at maintaining good energy resolution. A bright spot in this is that the gain stability of the devices constructed thus far has been very good. These facts lead to the following prescription for isotope identification.

- There will be no peak fitting employed. Instead a peak region for any given gamma energy will be chosen based upon laboratory measurements with strong sources. These peak regions have been shown to be very stable *versus* time.
- These peak regions or windows will be used to determine the presence or absence of a particular gamma peak (and hence the isotope) by comparing the net counts in the window with 'background' counts. The criterion adopted for the MDA data given previously is that the net counts must equal or exceed 3σ of the 'background' counts.
- The 'background' counts are determined over a window width of FW50M (full width at 1/50 the maximum peak height) as determined from extensive laboratory characterizations. In practice a region adjacent to the peak window and higher in energy will be used to assess the background for most of the peaks in the library. The counts in this region, assuming there are no competing peaks present, are then normalized to the peak window in question via the background shape (see Figures 5, 6, and 7 and associated analysis). This normalized background is then subtracted from the gross counts in the FW50M region centered on the nominal peak and the net counts, if any, are then compared to three standard deviations of the normalized background to see if a peak is actually present.

  There are several exceptions to this method that are isotope dependant and are part of the software. In addition, secondary peaks may be used to verify the presence of a particular isotope, particularly if more than one isotope is found. Alternative peak regions may be assigned and examined if the spectrum complexity indicates some uncertainty.
  As an example, if a source shows a peak at 356 keV the software will look for a similar height peak at 414 keV whose presence may indicate that ^{239}Pu is the isotope present and the lower energy peak should have been 374 keV. In this example the presence of neutrons is also needed before ^{239}Pu is declared. If the nominal 374 peak net counts do not match the counts expected at that energy from the 414 keV counts then it may be that ^{133}Ba is also present. If there is no peak at 414 keV (and no neutrons) then it is likely that ^{133}Ba is the isotope present. The presence of ^{133}Ba is confirmed if there is an 80 keV peak. ^{133}Xe could contribute to the 80 keV region, but would not show a peak at 365 keV. Thus there are a number of checks made on each peak found in a designated peak region to confirm what isotope is actually contributing to this region. There are similar restrictions placed on identification of all the other isotopes in the instrument table.
- The instruments adjust the collection time using gross counts to help maximize the peak counts for the automatic analysis used in the large complex instrument.
- There are 18 isotopes in the instrument library (15 in the small low power instrument). Each isotope has its own peak or peaks that are used for identification. All the common

SNM isotopes are present including ^{233}U and ^{237}Np; the common medical isotopes such as ^{99m}Tc, and ^{201}Tl for example are included; and, lastly, the low energy industrial isotopes such as ^{241}Am and ^{133}Ba are included. The CZT array has very poor detection efficiency for ^{137}Cs and ^{60}Co and these are handed off to the 2 x 2 NaI for identification. The small low power instrument does include ^{137}Cs in the identification code, but, in practice, this is identified only for tens of μCi sources at 20 cm or less for >10 minutes collection time.

Appendix A

Representative CZT Gamma Spectra

This appendix presents gamma spectra derived from a number of different CZT crystals and arrays of crystals. The differences between these spectra are:

- Most spectra were taken with an array of eight crystals in two configurations: (a) four pairs of crystals, each pair with its own linear amplifier and ADC followed by digital summation of the four separate spectra, and (b) eight crystals paralleled into one amplifier and ADC resulting in one spectrum. These two configurations will thus differ in energy resolution due primarily to analog summing *versus* digital summing. The overall efficiencies should be the same.

- A few spectra are given taken with an early CZT crystal with a 'spot' electrode design. This gave better energy resolution, but very poor efficiency. This low efficiency is due to the use of only one CZT crystal and the 'spot' electrode was only 1 mm in diameter compared to the 5-mm square 'cap' electrode used in the other spectra.

The first group of spectra compares a 2×2 NaI scintillator response with the 8-crystal CZT detector array (four pairs of two crystals each) for a number of isotopes and isotope mixtures. The second group of spectra compares the 'spot' electrode response for several different isotopes, and the third group of spectra compares the 8-crystal array response utilizing different support electronics for several isotopes.

Comparisons between 2 x 2 NaI and CZT Spectra

The first two spectra below compare a 2×2 NaI scintillator response with the CZT array response to the SNM isotope ^{233}U.

Figure A-1 shows that the CZT array energy resolution allows easy separation of the Bi and Pb x-rays, and verification of the adjacent peaks from ^{208}Tl and ^{212}Bi near 300 keV.

Figure A-2, an extended energy range display of Figure A-1, shows the 583 keV peak that may be used for identification together with the 238 keV peak. In actual practice these peaks are also in the background from natural thorium, but the ^{233}U gammas from any reasonable size source will overwhelm the background gammas.

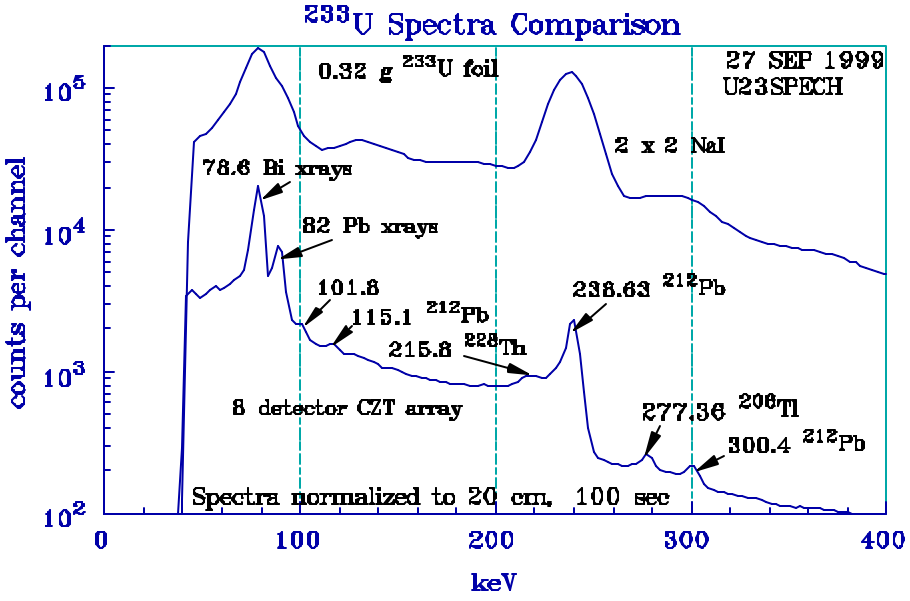


Figure A-1. Comparison between 2 x 2 NaI and CZT array.

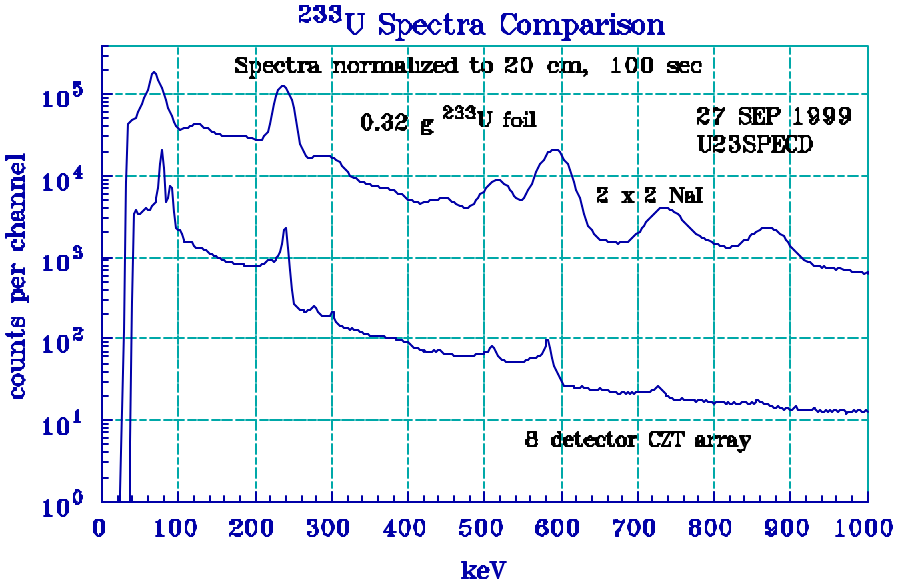


Figure A-2. Extended energy scale of Figure A-1.

Figures A-3 and A-4 show a comparison between a 2 × 2 NaI and an 8-crystal CZT array for a mixture of isotopes: ^{131}I and ^{239}Pu. The 2 × 2 NaI spectra illustrate that ^{131}I and ^{239}Pu cannot be differentiated. The CZT spectra show that the ^{131}I and ^{239}Pu peaks near 370 keV are still difficult to resolve, but the 414 keV peak due to ^{239}Pu can now be seen and will help identify ^{239}Pu as part of the source mixture.

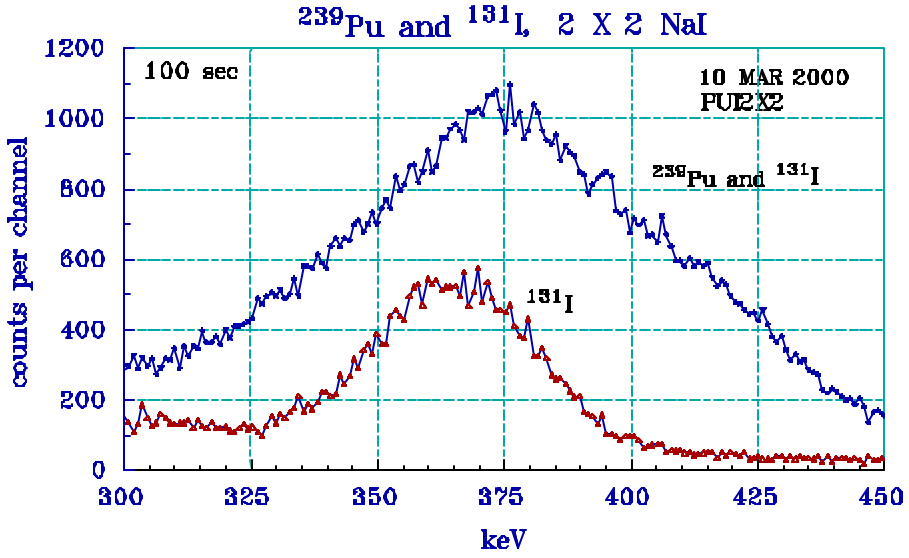


Figure A-3. 2 X 2 NaI spectra, ^{131}I and ^{239}Pu.

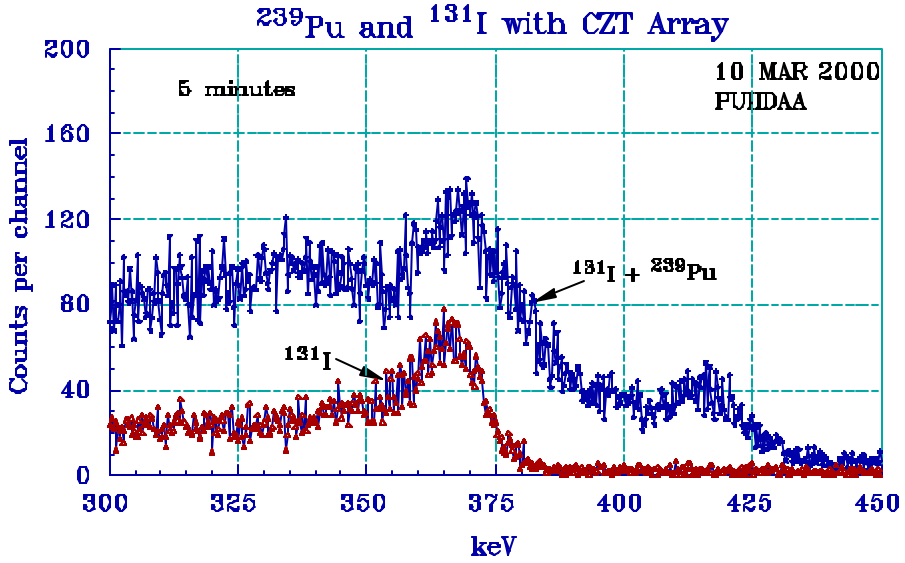


Figure A-4. CZT array spectra from ^{131}I and ^{239}Pu.

Figure A-5 shows another comparison between a 2 × 2 NaI scintillator and the CZT array. In this figure the 2 × 2 NaI scintillator produces a broad ill-shaped peak near 375 keV, while the CZT spectrum will allow quantitation of individual peaks leading to a more positive identification.

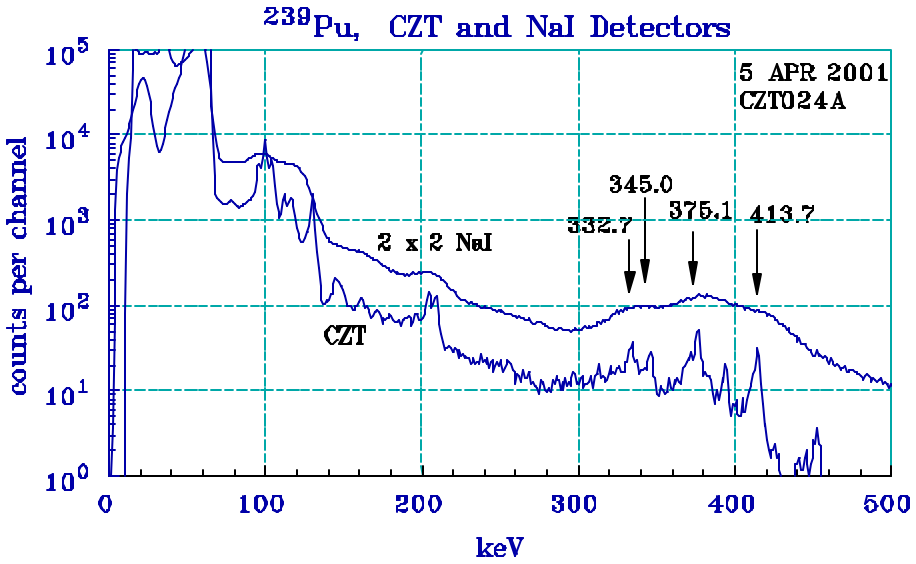


Figure A-5. Comparison between 2 x 2 NaI and a CZT array.

Spot Electrode Spectra

The spectra in this section (Figures A-6 through A-13) were taken with a single 5-mm diameter by 5-mm-thick CZT crystal with a so-called spot electrode. This spot electrode was 1 mm in diameter. All spectra were taken with a special STL preamp and NIM-BIN electronics.

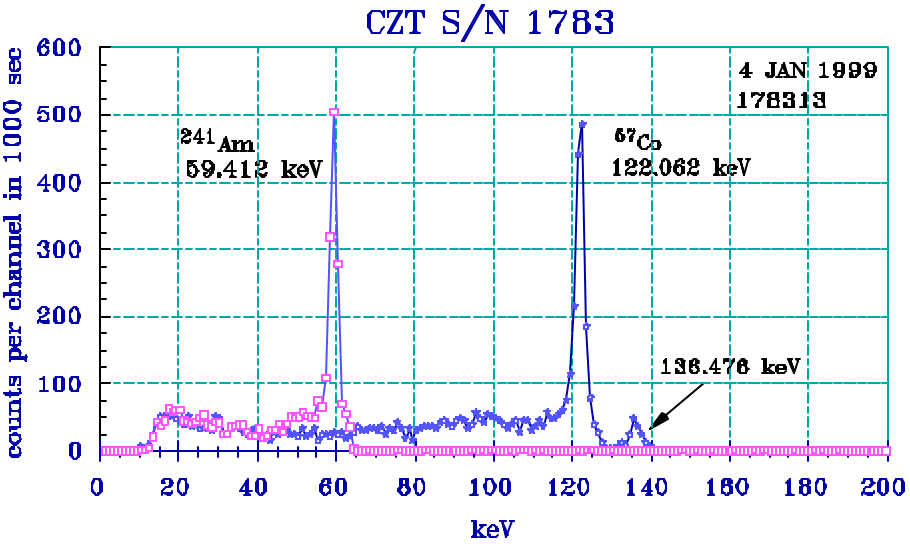


Figure A-6. ^{241}Am and ^{57}Co spectra.

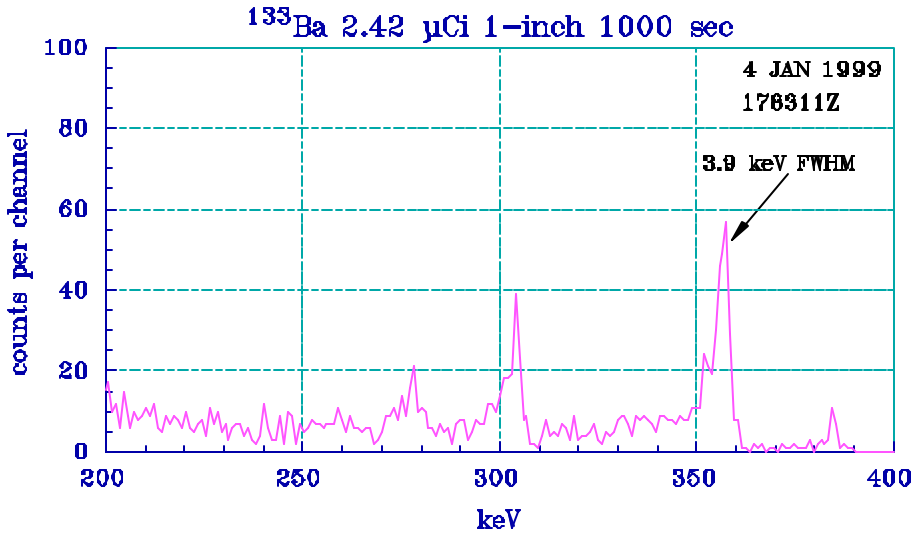


Figure A-7 ^{133}Ba spectrum.

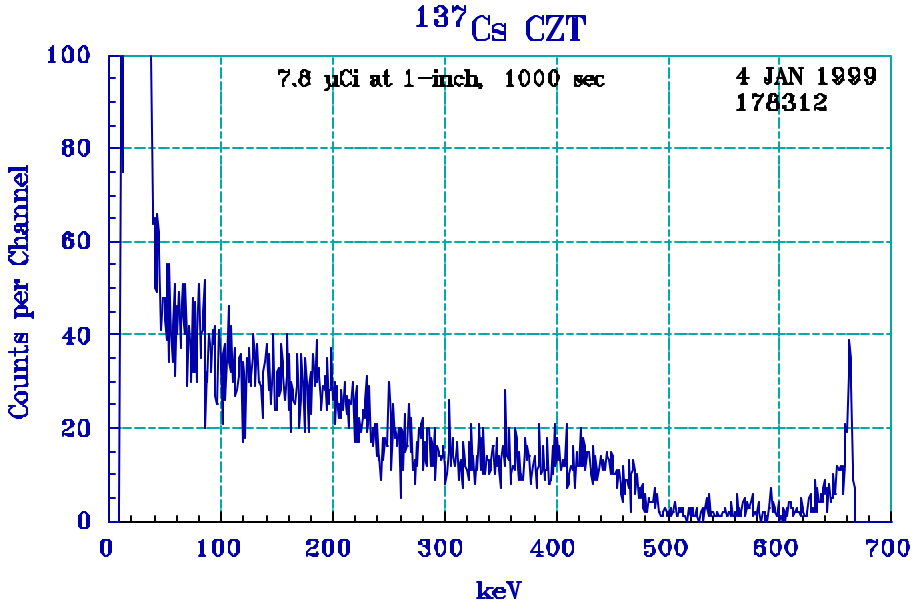


Figure A-8. ^{137}Cs spectrum.

The preceding three figures (A-6, A-7, A-8) present spectra from some of the most common laboratory sources. The next group of figures (A-9, A-10, A-11, A-12, A-13) shows spectra from two SNM sources.

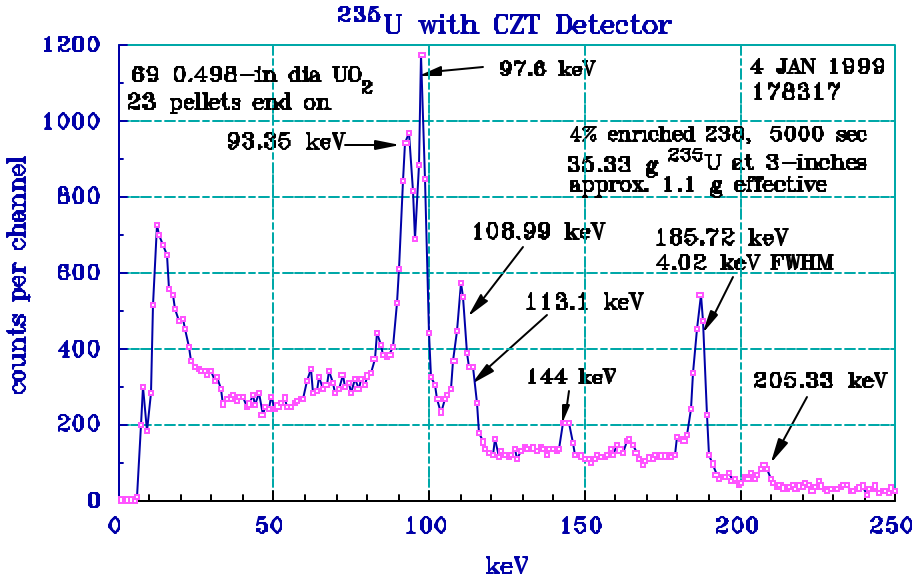


Figure A-9. ^{235}U spectrum.

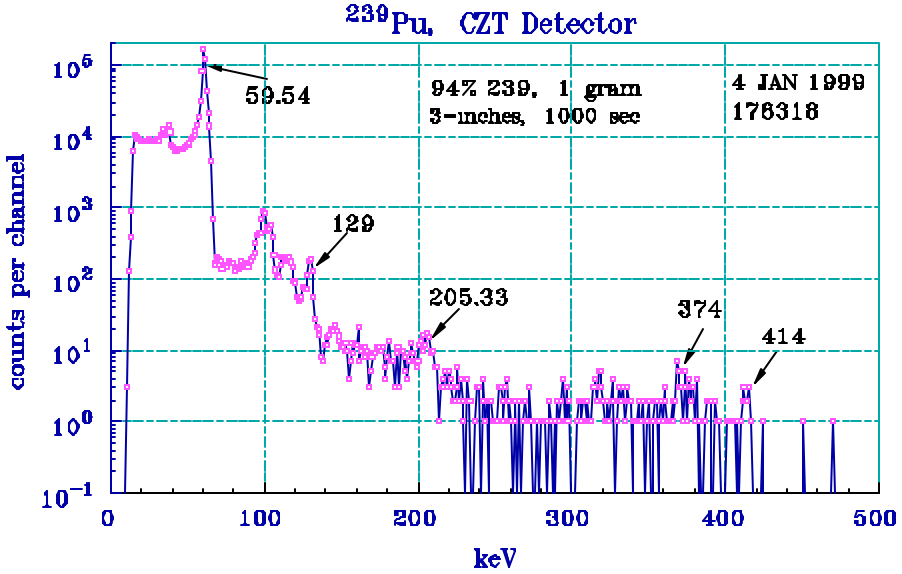


Figure A-10. ^{239}Pu spectrum, 1000 seconds.

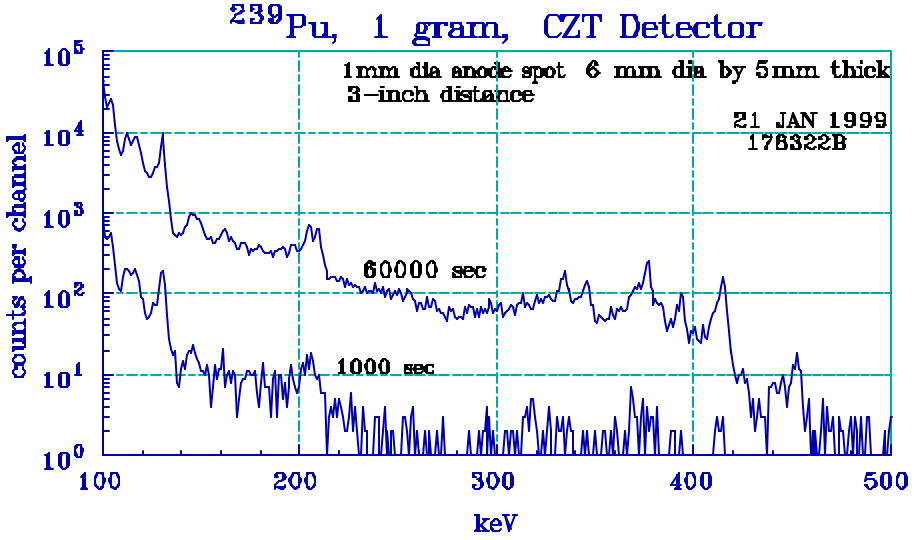


Figure A-11. ^{239}Pu contrasting two different counting times.

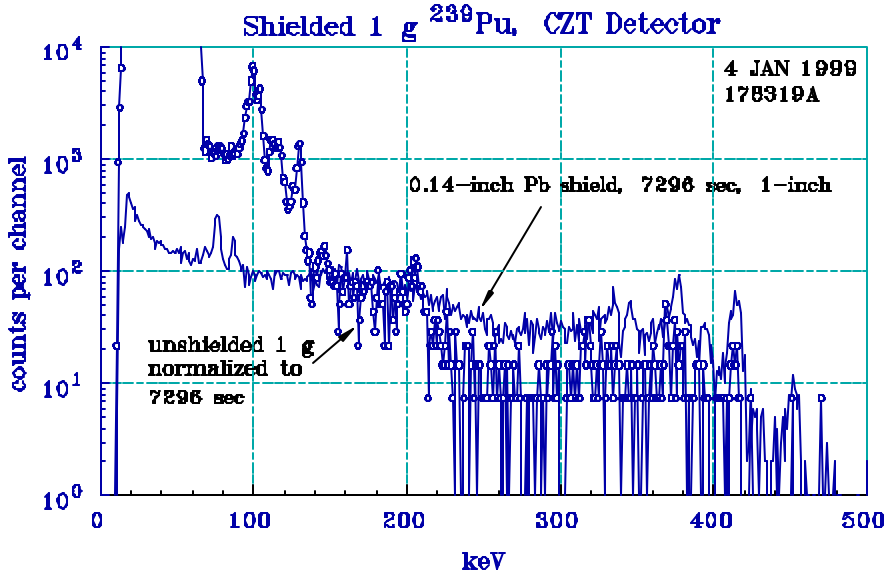


Figure A-12. ^{239}Pu spectrum showing effect of Pb shield.

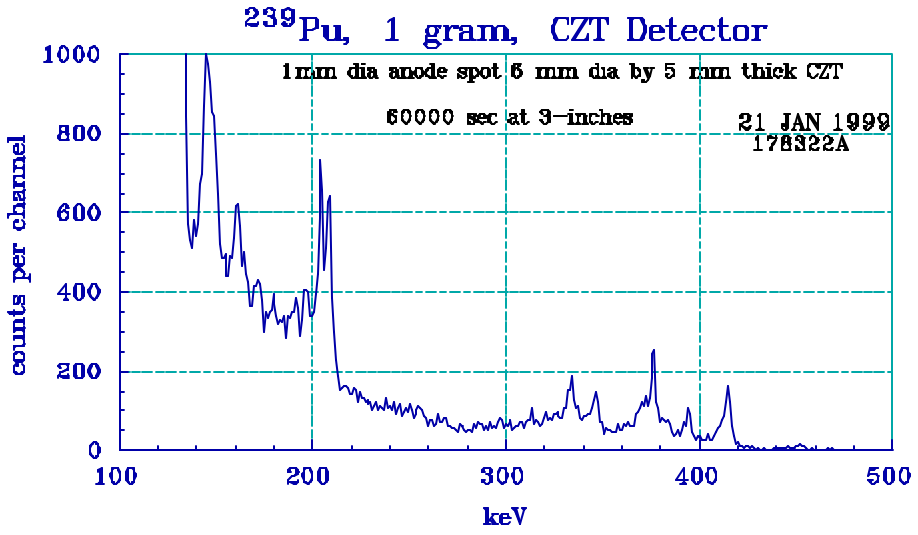


Figure A-13. Linear plot of ^{239}Pu spectra.

The preceding figures (A-9 through A-13) derived from SNM illustrate the spectral detail that can be obtained with CZT detectors. In many cases this detail can be used to help identify the source material. Figure A-9 of ^{235}U shows peaks at 144 and 185 keV that will penetrate light shielding and permit isotopic verification. Note that this source was effectively 1.1 grams of uranium due to significant self-absorption.

Figures A-10 through A-13 were derived from a small 1 gram piece of ^{239}Pu. Note that the counting times are very long due, in some cases, to the small source size, and the very poor efficiency of this 'spot' electrode detector. The data in Figure A-10 was taken for 1000 seconds (about 16 minutes) and does have enough information in the 374 keV peak to identify ^{239}Pu. The 414 keV peak is too small to be useful however.

The effect of a thin shield of lead is shown in Figure A-12. The low energy gammas from ^{241}Am are eliminated, but the 374 keV peak is visible as well as the 414 keV peak. These would be sufficient to identify this isotope.

Eight Crystal Array Spectra from Hand-Held Instruments

The spectra in this section were taken with battery-operated portable hand-held electronics of two different types. The first few spectra used an instrument with four pairs of CZT crystals. Each pair had its own linear electronics and its own ADC. The instrument accumulated four spectra which were then digitally added together after gain and offset corrections were applied.

Figure A-14 presents an expanded part of spectra from two sources plotted together. These two sources can be separately identified due to the presence of a lower energy ^{133}Ba peak (302 keV energy, here at channel 1190) where the ^{131}I source has a valley. A more secure identification of the ^{133}Ba will use the ratio between the 302 keV peak and the 365 keV peak to verify the presence of ^{133}Ba and not another isotope.

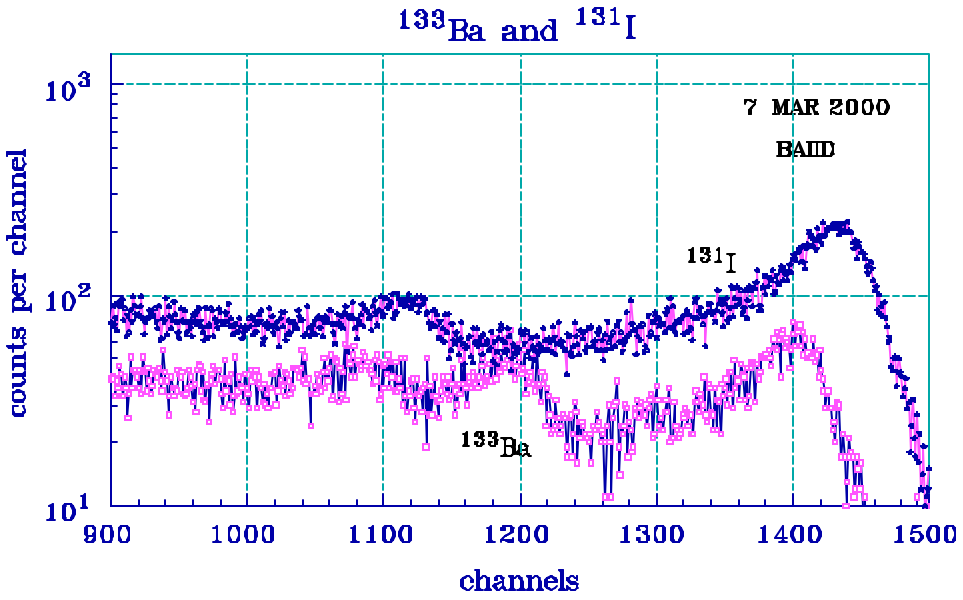


Figure A-14. Comparison between ^{131}I and ^{133}Ba.

The next four spectra (Figures A-15, A-16, A-17, A-180) were derived from common medical isotopes: ^{111}In, ^{67}Ga, ^{99m}Tc, and ^{201}Tl. In each of these cases the unique spectral shape allows ready identification.

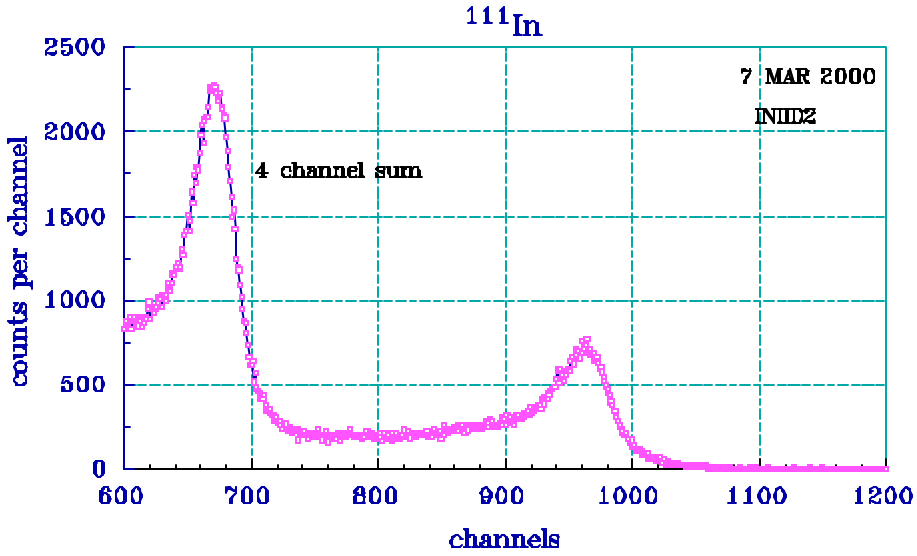


Figure A-15. ^{111}In, a medical isotope.

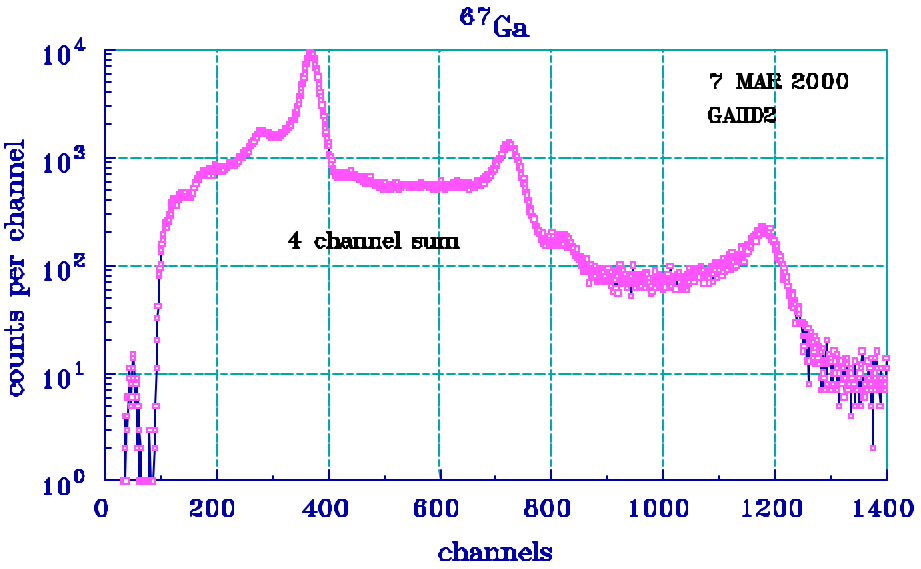


Figure A-16. ^{67}Ga, a medical isotope.

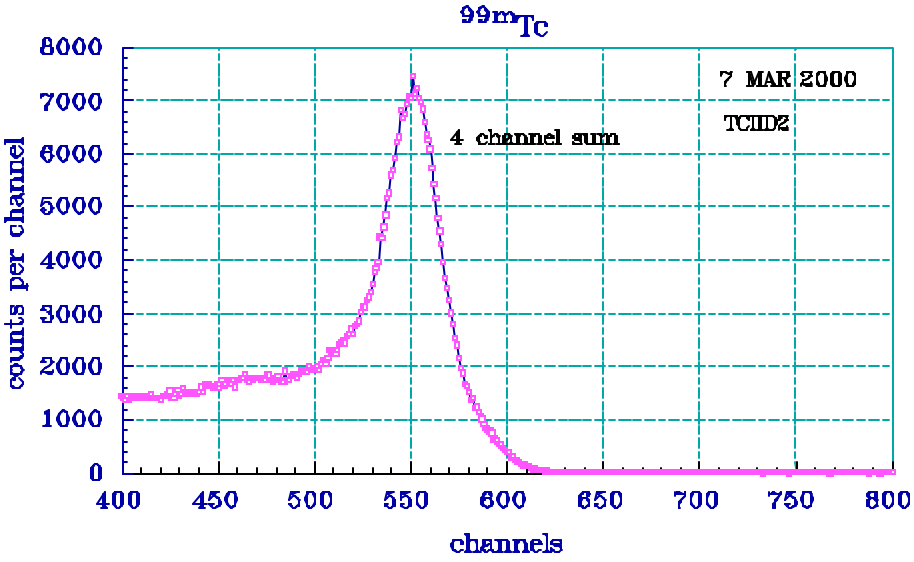


Figure A-17. ^{99m}Tc, a medical isotope.

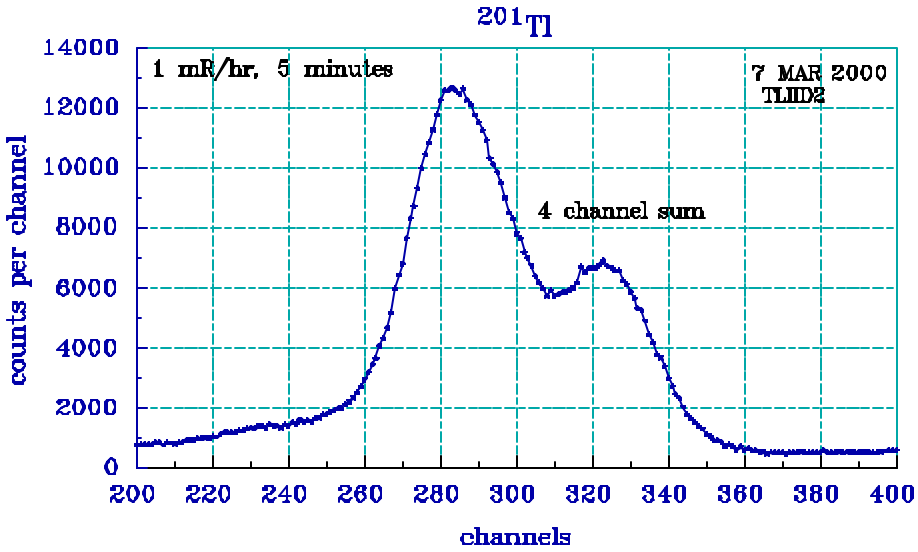


Figure A-18. ^{201}Tl, a medical isotope.

These medical isotope spectra, and all the preceding spectra in this section, are the result of digital summation of the individual spectra from the four pairs of CZT crystals in the portable instrument. All collection and processing was done in the instrument before the data were downloaded to a PC.

The next three figures (A-19, A-20, A21) present data from an 8-crystal low-power instrument that had all eight crystals paralleled into one preamplifier. This saved some analog power by eliminating three amplifier chains plus three ADCs, but at the expense of a degradation in resolution at the low energy end. This is illustrated by comparing the ^{241}Am resolution from Figure 6 in this paper, about 5.1 keV FWHM, *versus* 7.4 keV FWHM shown in Figure A-19. The higher energy peaks from ^{133}Ba at 356 keV and from ^{137}Cs at 661 keV show less resolution degradation (if any) since the noise contribution from the analog summing process is mostly made up of very small pulses and thus is a smaller fraction of the higher energy peaks.

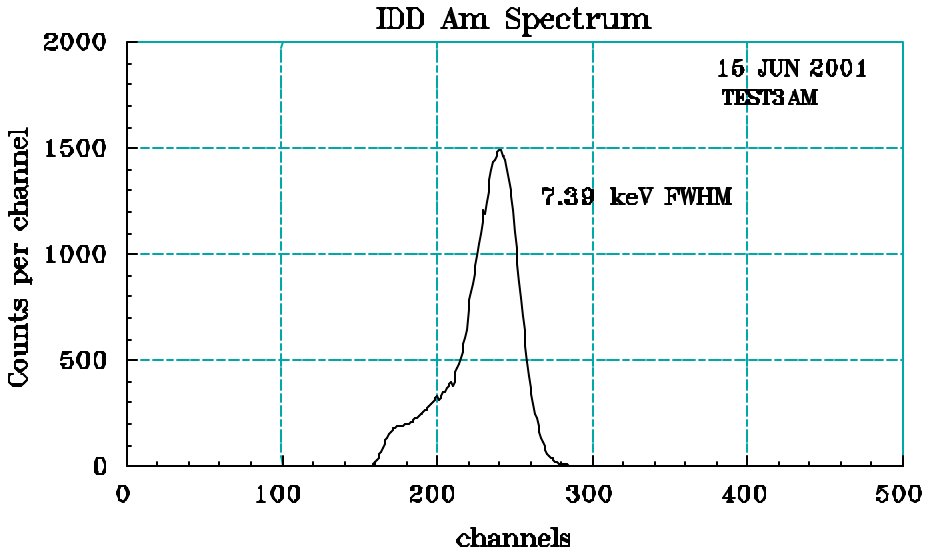


Figure A-19. ^{241}Am spectrum from IDD instrument.

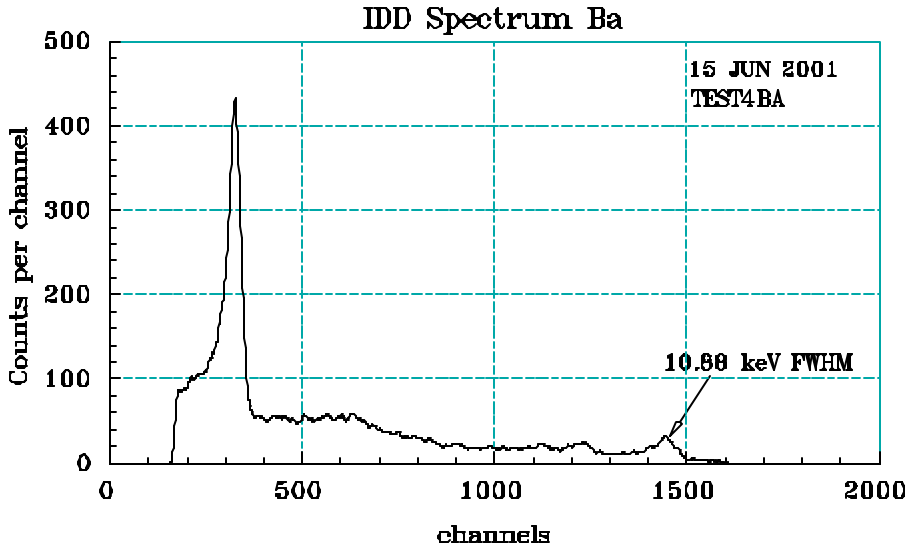


Figure A-20. ^{133}Ba spectrum from IDD instrument.

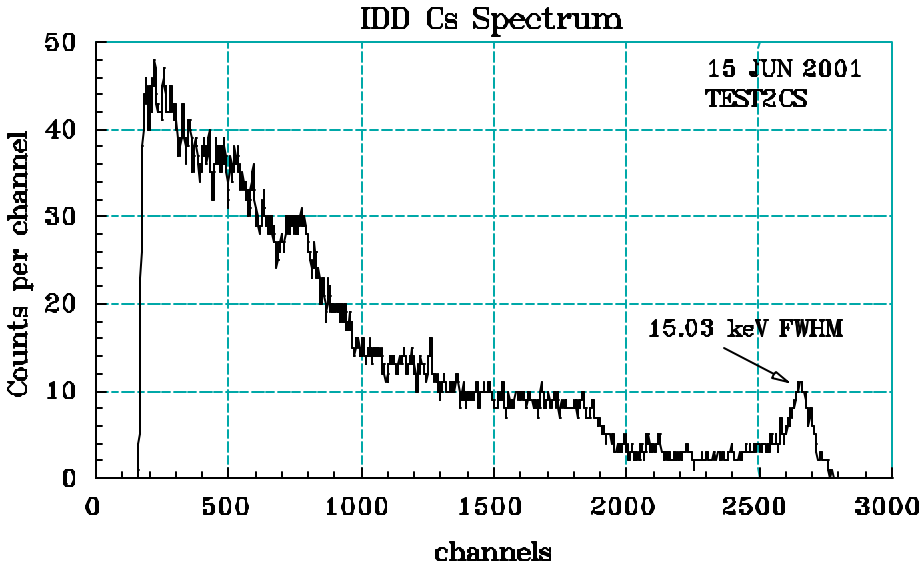


Figure A-21. ^{137}Cs spectrum from IDD instrument.

Appendix B

Commercial CZT Spectrometers

There are only a few commercial vendors of CZT spectrometers at the present time. Most of these vendors use CZT material manufactured by eV Products, either in the form of finished detectors, or raw material. This Appendix lists some of the available products together with spectra we have acquired from a few of the instruments.

AMPTEK

AMPTEK has produced CZT detectors for a number of years. They have several models including a thermoelectric cooled version. One model has built-in pulse shape analysis to improve energy resolution by eliminating slow rise time signals caused by poor collection of charge within the crystal. These instruments are typically self-contained with an internal high voltage power supply.

All of the AMPTEK CZT detectors are single crystals and, as such, have poor efficiency. In addition, the pulse shape analysis circuitry discards half of all pulses reducing the efficiency even more.

A selection of CZT spectra taken with AMPTEK instruments is presented in Figures B-1 through B-6.

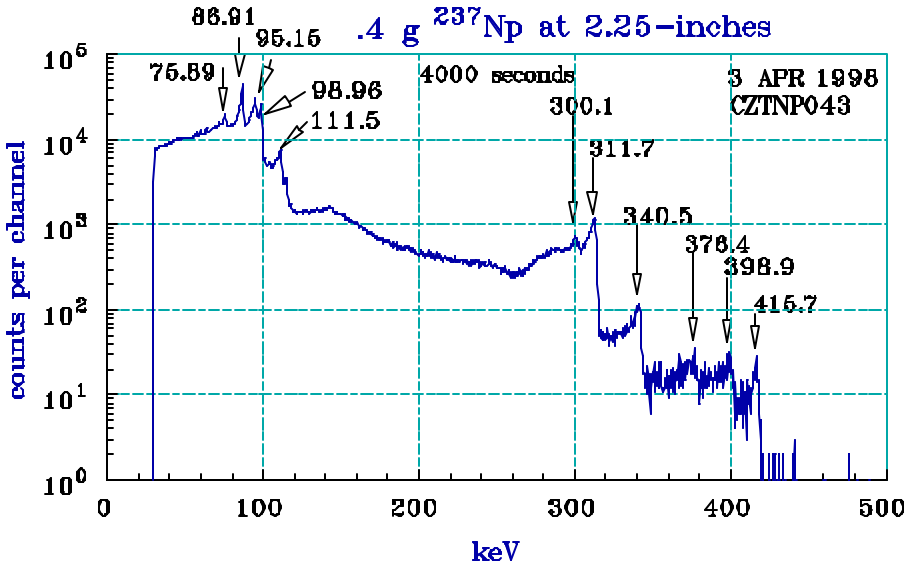


Figure B-1. ^{237}Np spectrum.

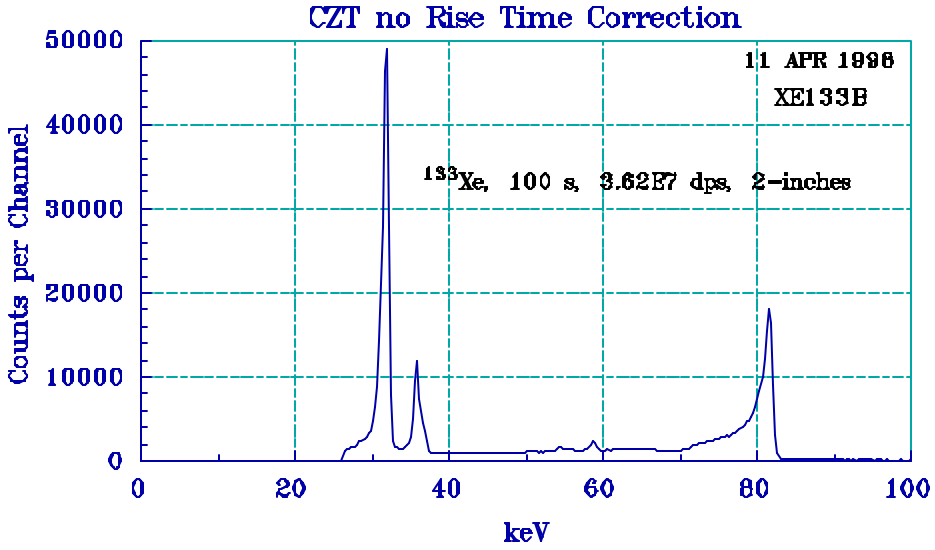


Figure B-2. ^{133}Xe spectrum.

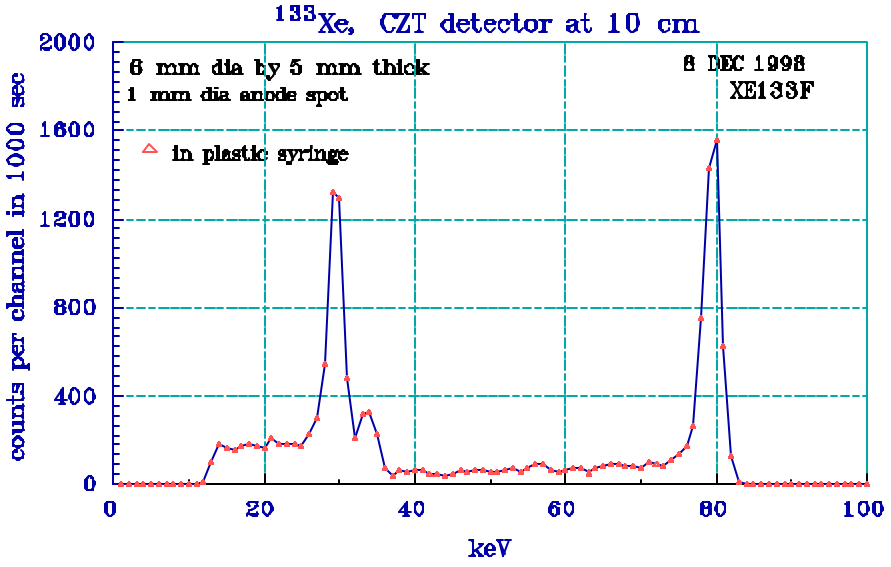


Figure B-3. ^{133}Xe spectrum.

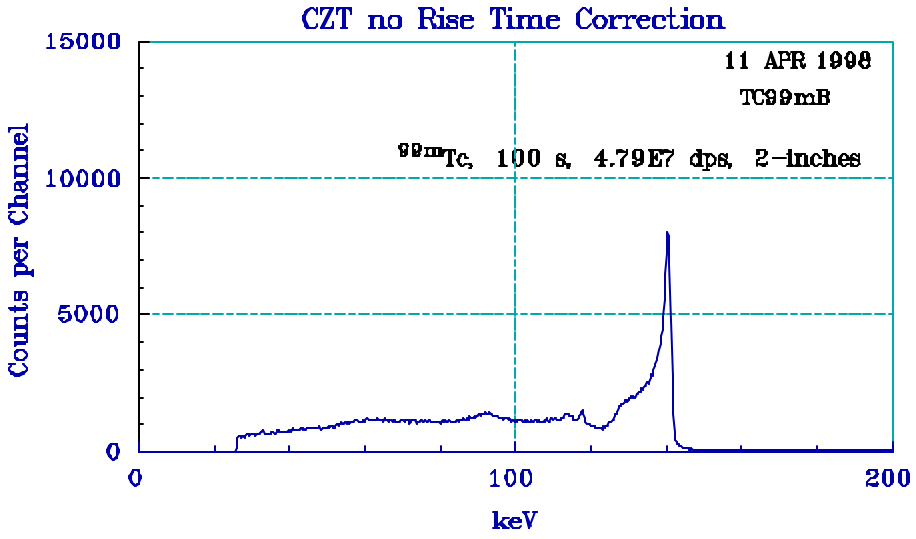


Figure B-4. ^{99m}Tc spectrum.

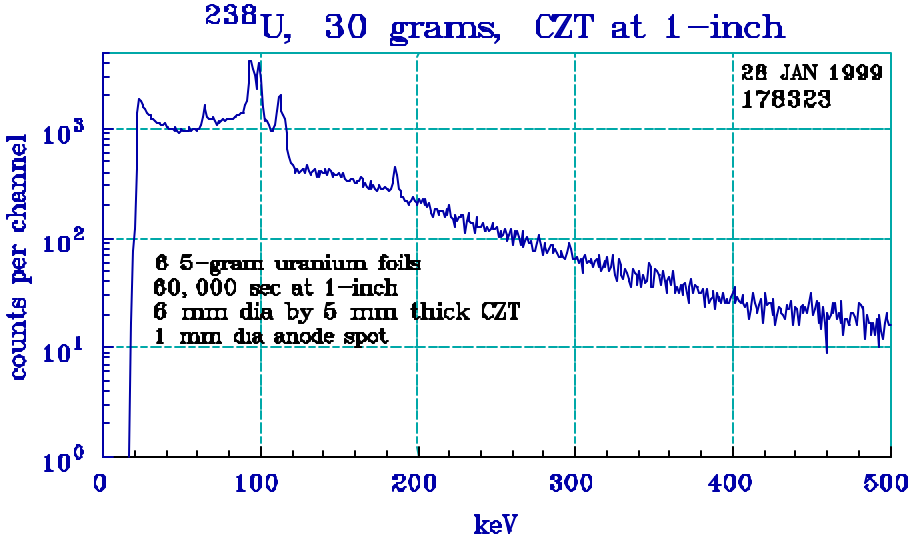


Figure B-5. ^{238}U spectrum.

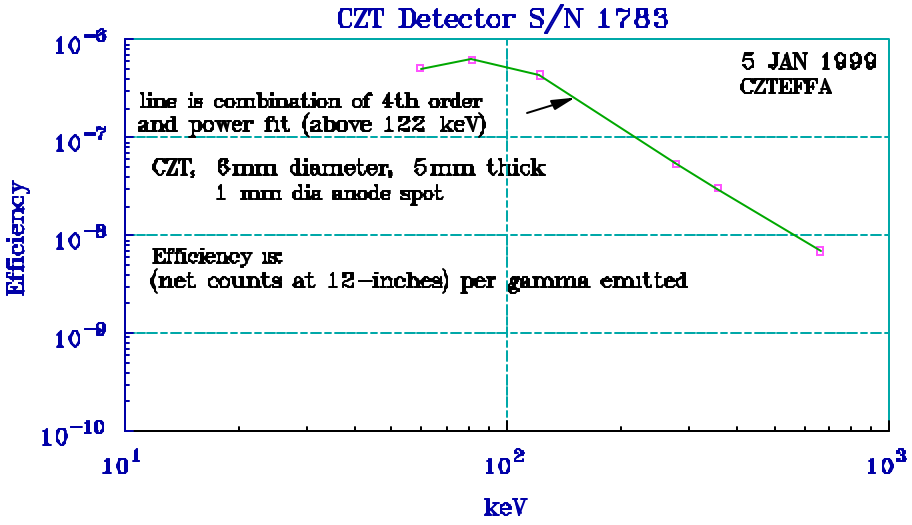


Figure B-6. CZT efficiency, spot electrode detector.

eV Products

eV Products, the major vendor of CZT material in the United States, also manufactures a single crystal CZT detector called SPEAR. This instrument uses one of the same type of CZT crystals that we have incorporated into the CZT arrays. The eV Products instrument is packaged in a small cylindrical housing 12 mm in diameter and 89 mm long. It requires ± 2 VDC and high voltage to operate. The SPEAR instrument will have an efficiency identical to one of the crystals used in the CZT array.

RITEC, Ltd.

This company, based in Riga, Latvia, uses a specially modified eV Products CZT crystal having a hemispherical electrode on one face of the crystal, and a 'spot' electrode on the opposite face. This produces a shaped electric field within the crystal that is expected to produce better resolution spectra, particularly for higher energy gammas.

We have been able to examine this device, and have obtained some spectra through the courtesy of Rolf Arlt of the International Atomic Energy Agency (IAEA). These spectra are shown in Figures B-7, B-8. and B-9.

The RITEC detector is packaged in a cylindrical housing approximately 23 mm in diameter and 95-mm long including preamplifier. This instrument requires external power (±12 VDC) and external high voltage. The CZT crystal has a sensitive volume of 0.5 cm^3 and is thus comparable in efficiency to the eV Products instrument and one crystal of our CZT array.

Comparing this RITEC instrument with the 8-crystal array we find that the array has better resolution up to approximately 200 keV, marginally better up to 400 keV, and worse

resolution at 662 keV, the ^{137}Cs peak. The following spectra are representative of the RITEC instrument response when used with a portable battery-operated spectrometer.

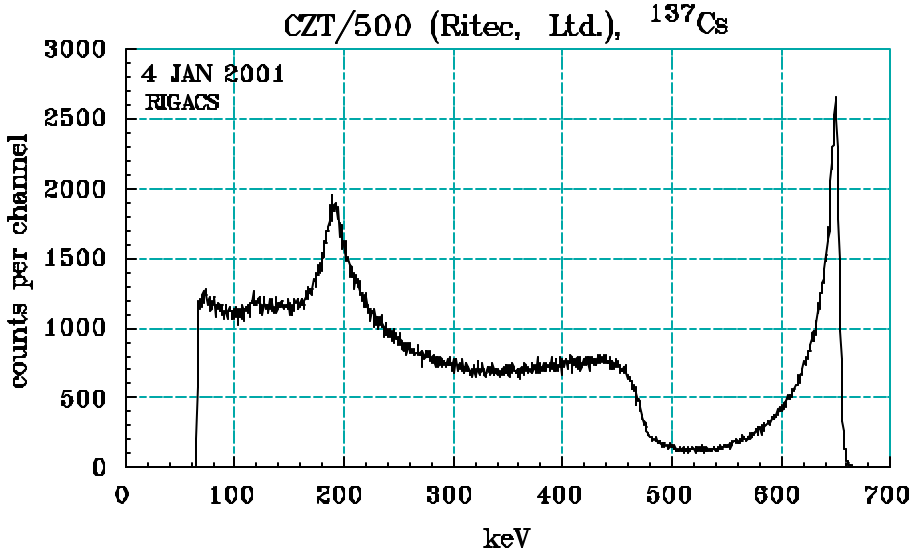


Figure B-7. ^{137}Cs spectrum.

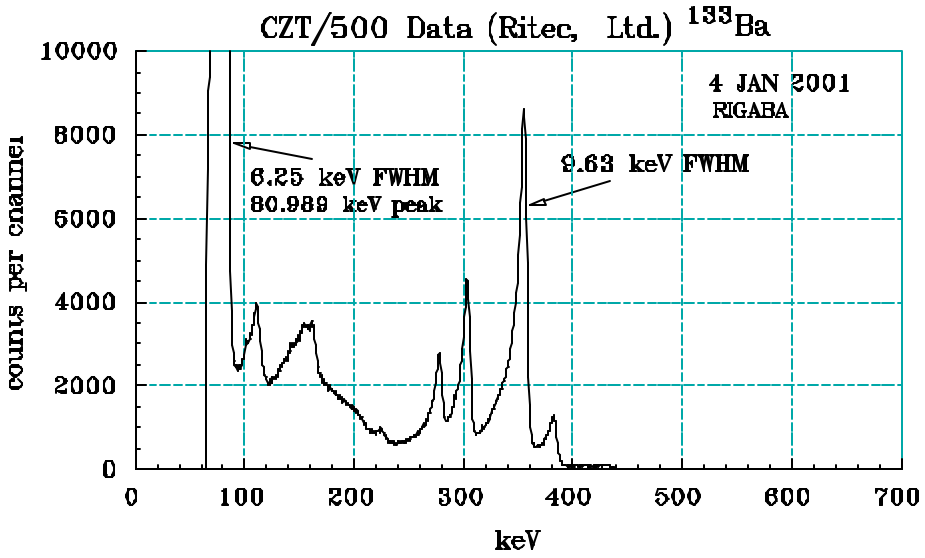


Figure B-8. ^{133}Ba spectrum.

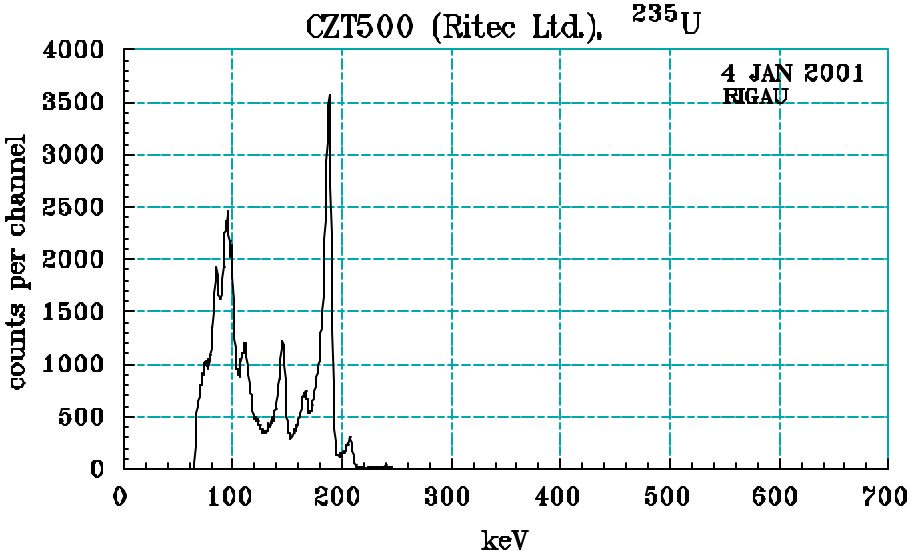


Figure B-9. ^{235}U spectrum.

XRF Corporation

The XRF Corporation offers the ICS-4000 and the ICS-4000e. These instruments have a $10 \times 10 \times 2$ mm thermoelectrically cooled CZT crystal as the detector. The design incorporates a high voltage power supply, analog and digital processing, and a 4096 channel ADC. The basic instrument is a hand held spectrometer with an LCD providing a user interface. The sensitivity is not given, but the ^{137}Cs energy resolution is stated to be about 11 keV FWHM. Based upon crystal area the sensitivity should be half as great as the 8-crystal array.

Appendix C

CZT Temperature Dependence

Gamma ray spectrometers should have good stability *versus* temperature. This requirement is important if the spectral data are to be used for quantitative analysis, for example isotope identification. Temperature effects usually show up as shifts in peak position in the spectrum. This can broaden the effective energy resolution or even cause misidentification of peaks if the energy shift is large enough.

The 8-crystal CZT module, including all analog electronics and the HVPS, were subjected to varying temperatures from -40ºC to +40ºC. The gain shift was measured by recording the position of the nominal 88 and 356 keV peaks from a ^{133}Ba source. Heating and cooling were done in an environmental chamber with at least 15 minutes 'soaking' at each new temperature.

We found that the output of the CZT crystals was reasonably constant at all temperatures except below -30ºC. At a temperature of -40ºC the output went to zero. A small resistor heater and a temperature controller were incorporated onto the PC board. This circuitry added a little heat to the sealed module below about -20ºC and permitted operation to -40ºC. The gain stability data obtained from the CZT module are shown in Figure C-1.

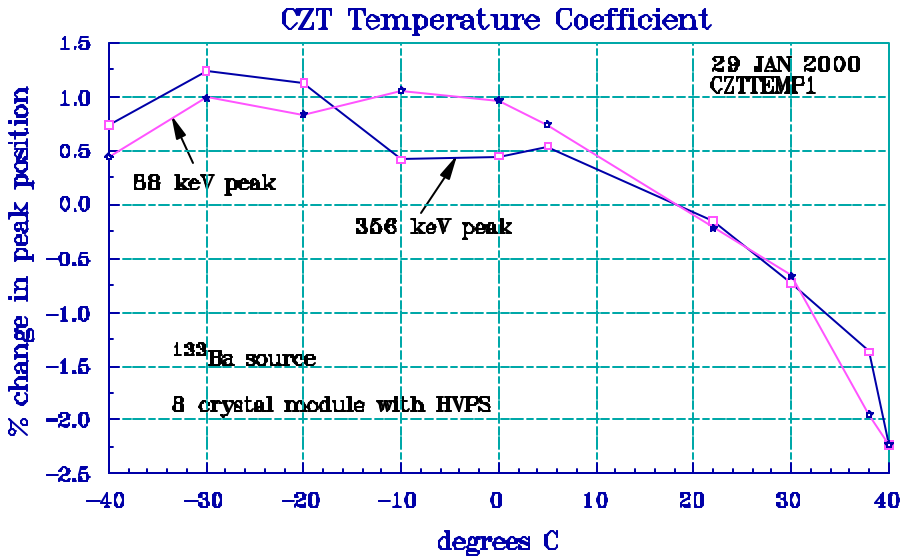


Figure C-1. CZT gain temperature dependence.

The worst case gain change is -2.5% at +40ºC compared to the average performance over the whole range from -40ºC to +40ºC. This represents about 8 keV at the 356 keV Ba peak. The change from room temperature (+22ºC) is about 2% or 7 keV. These temperature effects are fairly small and are comparable to the FWHM found using laboratory electronics, and about half of the FWHM using portable battery operated electronics.

The relatively small gain change with temperature implies that, in general, there may be a broadening of the energy resolution during temperature changes, but no real risk of peak misidentification. We expect to improve the gain *versus* temperature response somewhat in future designs.

The peak energy resolution at fixed temperature steps was also measured during the temperature testing. These data are shown in Figure C-2.

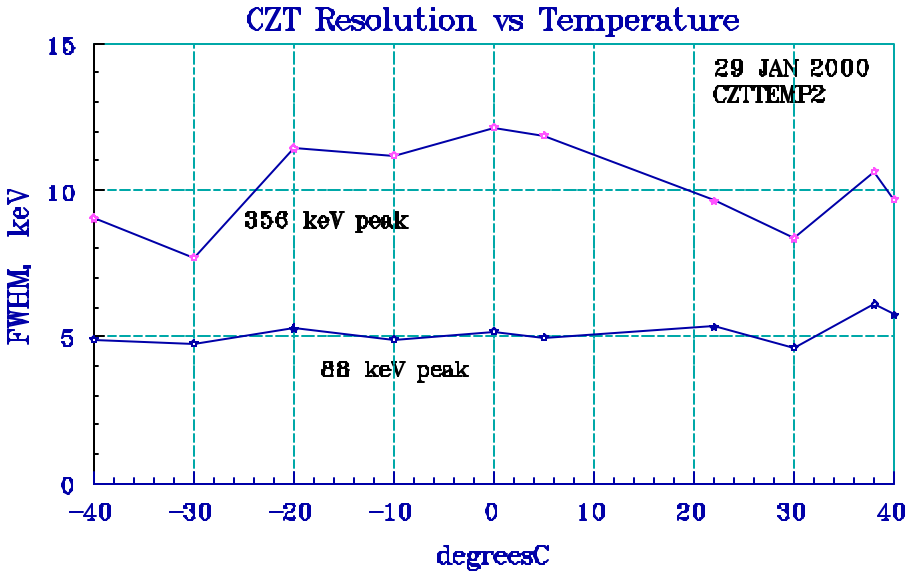


Figure C-2. CZT energy resolution *versus* temperature.

There is no real trend in detector resolution *versus* temperature. This suggests that the overall temperature effects, both in gain and resolution, are actually small from a practical point of view.

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