COMPTON SUPPRESSION SYSTEMS FOR ENVIRONMENTAL MEASUREMENTS

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ABSTRACT

The configuration and performance characteristics of a Compton Suppression System is described. System optimization is described for determination of the timing coincidence spectrum and position of the primary detector within the guard detector. Suppressed and unsuppressed spectra are presented for ^{137}Cs and the mixed ^{125}Sb-^{154}Eu-^{155}Eu sources. Background reduction, peak-to-background enhancement and peak-to-Compton performance for seven HPGe detectors ranging in size from 7 to 64.2% relative efficiency is reported. Performance as a function of relative efficiency is also reported.

Unsuppressed to suppressed background reduction in excess of 14:1 was obtained for non-peak regions near 700 keV. Using ^{137}Cs, Peak-to-Compton$_{edge}$ values were as high as 940:1 and Peak-to-Compton$_{plateau}$ values were as high as 880:1 for the suppressed system. The peak-to-total area ratio was improved by a factor of 2 for most detectors. Peak-to-background improvements for the ^{125}Sb lines ranged from 6 to 12, while those for ^{154}Eu-^{155}Eu lines ranged from less than unity to about 3.5:1.

Introduction

Environmental measurements often require detection systems with enhanced peak-to-background performance. A variety of techniques have been applied including the use of large HPGe detectors with excellent Peak-to-Comption ratios, special shielding to reduce external sources of radiation and active shielding techniques. This paper discusses the configuration and performance of a Compton Suppression System with small to medium HPGe detectors with emphasis on environmental measurements.

Compton suppression is an active shielding technique. The primary detector is surrounded by a guard detector. If coincident events are recorded in both detectors, the primary detector event is rejected. This enhances the signal-to-background ratio which directly enhances the system sensitivity and lowers the minimum detectable activity.

Compton Suppression System Configuration

A block diagram of the Compton Suppression System is shown in Fig 1. The primary detector is a HPGe photon detector. The guard detector consists of a 9"x9" NaI axial annulus with 4 photomultiplier tubes (PMTs) and a 3"x3" NaI plug detector. The HPGe detector is inserted into one end of the annulus and the NaI plug detector is inserted into the other end. Samples are placed inside the annulus between the HPGe and the NaI plug detectors. The combined HPGe-NaI detector system is housed in a 14"x14"x30" shield constructed of 4" lead bricks lined with 0.020" Cd and 0.060" Cu sheets. The shield top is on rollers for access.

There are several instrumentation chains in the Compton Suppression System. One output from the HPGe preamp is processed by an energy chain to collect an unsuppressed spectrum using a Spectroscopy Amplifier (672), a Multi-Channel Buffer (918A MCB) and a Spectrum Stabilizer (990). The second preamp output goes to a second energy chain and to the HPGe timing chain. The HPGe timing chain consists of a Timing Filter Amp (579 TFA) and a Constant-Fraction Discriminator (583 CFD). The NaI timing chain input signal is formed by summing all PMT anode signals into a TFA (579) followed by a CFD (583). Data acquisition is controlled by the IBM-PC using MCA Emulation Software (Maestro-II).

The Time-To-Amplitude Converter Single-Channel Analyzer (TAC/SCA, 567) performs the coincidence function. The TAC Start signal is taken from the HPGe timing chain since only events in the primary detector are subject to suppression. The Stop signal is from the NaI timing chain delayed by the Gate Delay Unit (416A). A typical timing spectrum is shown in Fig 2. The peak at the far right results from coincidence between the plug detector and the HPGe detector. The larger peak at the right results from the coincidence between the annulus and the HPGe detector. The sloping region in the center of the spectrum is due to slow rise time pulses and represents real coincidence events. A coincidence output signal is formed by the SCA. The SCA window should cover the entire coincidence time as shown in Fig 2.

Each instrument in the Compton Suppression System must be optimized for maximum performance. The energy chains require selection of time constant (6 us for HPGe), gain and PZ adjustment (the 672 has an Auto PZ feature). The MCBs are operated at 8k conversion gain and the Spectrum Stabilizers are set-up for normal operation per the manual. Both the NaI and the HPGe TFAs are typically set for no Integration and 500-ns Differentiation. Other settings may be required for high rate or high noise environments. The HPGe CFD operates in the Integral Mode with nominally 24-30 ns CFD Delay (425A). The NaI CFD operates in the Integral Mode with a CFD Delay (425A) selected equal to the rise time of its input signal which can approach 100 ns for a large NaI annulus. Both CFD energy thresholds are set at nominally 50 keV, below the lowest energy range of interest. This threshold adjustment is set by collecting an energy spectrum from the HPGe or NaI detector in an MCB gated by the corresponding CFD.[1,2]

The NaI CFD output must be delayed (416A) sufficiently, up to 1 us, to obtain a complete timing spectrum with random background on both sides as shown in Fig 2. The TAC time range must be sufficiently long to cover the timing spectrum with 1 us a typical value. The TAC/SCA Lower Level and Upper Level are selected to bracket the complete timing spectrum. The TAC/SCA output pulse is delayed and made sufficiently wide (416A) to cover the peak of the MCB linear input signal of the suppressed spectrum.

Final system optimization requires collection of many suppressed and unsuppressed spectra. The single line of ^{137}Cs, 661.66 keV, is a common source for studying system performance. One procedure is to find the optimum location of the HPGe detector in the NaI annulus. Fig 3 shows the variation in the Peak-to-Compton Ratio of the suppressed system as a function of the distance from the HPGe endcap to the edge of the NaI annulus. This curve is fairly flat with a peak at 2.5" where the geometric centers of the detectors are approximately lined up. For these measurements, the Compton plateau was calculated as the average counts per channel over the energy range 348-405 keV.

Compton Suppression System Performance

The Compton Suppression System was extensively tested using Detector #3 listed in Table 1. Measured using the ANSI/IEEE Standard 325-1986 procedures, this N-Type detector had a relative efficiency of 28.3%, a Peak-to-Compton ratio of 57.2:1 and a resolution of 1.86 keV measured at the 1.33 MeV line of ^{60}Co.

Fig 4 shows the unsuppressed and suppressed spectra for the system using a ^{137}Cs source. Three figures-of-merit are used: Peak-to-Compton plateau ($P/C_{plateau}$), Peak-to-Compton Edge (P/C_{edge}), and Peak-to-Total Area (P/A_{total}). The Compton plateau value is the average counts per channel for the energy range 358 to 382 keV, and the Compton edge is the average counts per channel for the energy range 475 to 481 keV. For the unsuppressed system, these figures-of-merit were $P/C_{plateau}$ = 121.2, P/C_{edge} = 98.4, and P/A_{total} = .21. The corresponding values for the suppressed system are 795.2, 864.9 and 0.43. Thus the Compton Suppression system had an Improvement Factor of 6.56 for the $P/C_{plateau}$, 8.79 for the P/C_{edge} and 2.05 for the P/A_{total}. This data is summarized in Table 2.

More realistic performance information can be obtained from a Compton Suppression System using a multi-line source such as a ^{125}Sb-^{154}Eu-^{155}Eu mixed source. This source is often used for the energy and efficiency calibration of HPGe detectors. Fig 5(a) shows the suppressed and unsuppressed spectra of the system using this source over the energy range 15-1800 keV, and Fig 5(b) shows the expended spectra over the energy range of 15-315 keV.

The function of a Compton suppression system is to reduce background counts without loss of peak counts. One measure of performance is its ability to reduce non-peak background counts. The suppressed and unsuppressed spectra shown in Fig 5 were evaluated in non-peak areas to determine the effect of Compton suppression on background reduction. Twenty-three non-peak regions were analyzed and the background counts-per-channel averaged over 20 channels was measured. The ratio of unsuppressed-to-suppressed background counts, or Background Suppression Ratio, is shown in Fig 6 as a function of energy. An order-of-magnitude reduction in background counts was obtained over the energy range of nominally 300 to 1100 keV. Above and below these energies, the effectiveness of background reduction was reduced.

A more sensitive measure of the effectiveness of a Compton Suppression System is to determine the enhancement of peak-to-background. To this end, the peak-to-background ratio of 21 peaks from the ^{125}Sb-^{154}Eu-^{155}Eu mixed source were evaluated. Using the MCA Emulation Software (Maestro-II), both gross and net peak areas were calculated. The net counts for each peak is the difference between the gross and background counts, and the peak-to-background ratio is the net peak counts to the background counts. These calculations were performed for both the suppressed and the unsuppressed spectra. The Improvement Factor for each peak was the ratio of the peak-to-background in the suppressed spectra to the corresponding value in the unsuppressed spectra. Results are plotted in Fig 7.

Three distinct sets of data are seen in Fig 7. Improvement factors for ^{154}Eu and ^{155}Eu range from less than 1 to nearly 4, while Improvement Factors for ^{125}Sb range from 6 to 12. This dramatic difference is expected since the ^{154}Eu lines are cften coincident and suppressed by the Compton Suppression System electronics. The ^{155}Eu lines are low energy lines, whgere the suppression is small. The Sb lines are not coincident and hence have greater Improvement Factors.

Compton Suppression System Performance vs Detector Efficiency

As reported by Paulus and Keyser[3] and by Keyser et al[4], a very effective way to enhance background suppression is to use very large HPGe detectors which can have very large Peak-to-Compton ratios. HPGe detectors with greater than 100% relative efficiency are available and they can have P/C ratios between 90 and 100:1 (measured at the 1.33 MeV line of ^{60}Co). Measurements were taken using ^{137}Cs and this Compton Suppression System with several detectors. An upper limit of the detector size (65%) is due to the inner diameter of the NaI annulus. A summary of performance is given in Table 2 and Fig 8.

Fig 8 shows the Compton Suppression System performance as a function of detector efficiency for 6 HPGe detectors, D1 through D6, listed in Table 1. Fig 8(a) shows the P/C_{edge} ratio ranged from 58.2:1 for a small detector (7%) to 102.7:1 for a large detector (62.9%) in the unsuppressed configuration. The corresponding suppressed system performance was 336.5:1 and 940.9:1.

The suppressed-to-unsuppressed Improvement Factor ranged from 5.8:1 to 9.2:1. For these measurements the Compton edge was measured as the average counts per channel over the energy range 475-481 keV and the conversion gain was 0.25 keV/Ch.

Fig 8(b) shows similar data for the $P/C_{plateau}$ performance of the system. For the unsuppressed system, the $P/C_{plateau}$ values ranged from 71.1:1 for the small detector to 131.0:1 for the largest detector. For the suppressed spectra, these values ranged from 312.8:1 to 880.6:1 giving suppressed-to-unsuppressed Improvement Factors ranging from 4.40:1 to 6.72:1. For these measurements, the Compton plateau was measured as the average counts per channel over the energy range 358-382 keV and the conversion gain was 0.25 keV/Ch.

Fig 8(c) shows the peak-to-total area performance of the system. Peak-to-total area ranged from 4.40:1 for the small detector to 6.72:1 for the large detector. The Improvement Factor remained nearly constant at 2:1. For these measurements, the total area was the sum of all converted events.

A second Compton Suppression System was built using a similar NaI annulus and plug with Detector D7 listed in Table 1. This N-Type HPGe detector was very similar to Detector D6 and very similar Compton suppression results. The unsuppressed $P/C_{plateau}$ was 158.7:1 and the suppressed value was 895.5:1 giving an Improvement Factor of 5.65:1.

Keyser et al[4] reported data on the background count rates in non-peak regions in the presence a mixed ^{125}Sb-^{154}Eu-^{155}Eu source for a large number of HPGe detectors. This data was reported as both count rates and count rates per percent efficiency of the HPGe detector. While background count rates increased with detector size, the count rates per percent efficiency decreased. This reduction was attributed to the increase in Peak-to-Comption ratio with increasing relative efficiency. Similar measurements were performed with the Compton Suppression System.

Fig 9 shows the Background Count Rate as a function of detector efficiency for Detectors D1 through D4 and D6 listed in Table 1. Background count rates were measured in non-peak regions averaged over 20 channels at 325, 540, 762 and 936 keV. These energy ranges correspond to those reported by Keyser*. The mixed ^{125}Sb-^{154}Eu-^{155}Eu source was placed on the endcap of the HPGe detector. Fig 9(a) shows the background count rate for the unsuppressed spectrum and Fig 9(b) shows the background count rate for the suppressed spectrum. Note that Fig 10(b) has a X10 smaller vertical scale. Improvement Factors followed the same trend shown in Fig 6, and were greatest for the 540 and 762 keV background regions, ranging from about 10 to 16. Improvement Factors were about 8 in the 325 keV region and about 10 in the 936 keV region. Improvement factors were relatively independent of detector efficiency.

Fig 10 shows the Background Count Rate per Percent Efficiency as a function of detector efficiency. Fig 10(a) is for the unsuppressed spectrum and Fig 10(b) is for the suppressed spectrum. Note that Fig 10(b) has a X10 smaller vertical scale. These measurements agree with Keyser's work indicating that the background counts in large detectors increase more slowly than the peak counts. This trend is continued and enhanced in the suppressed system.

Conclusions

Compton Suppression Systems can greatly enhance the peak-to-background performance of a detection system. Background reduction in excess of 10:1 is achievable under a variety of conditions. Peak-to-$Compton_{plateau}$ ratios can be improved over a factor of 6:1 and Peak-to-$Compton_{edge}$ ratios can be improved over a factor of 8:1 when measured with ^{137}Cs. Similar Peak-to-Compton improvements are possible with multi-line sources having non-coincident emitters. The improvements in detection limits by using large HPGe detectors reported by Keyser et al[4] is confirmed and shown to carry over to Compton Suppressed Systems.

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TABLE 1. HPGe DETECTOR CHARACTERISTICS

DET NO	SN	DIA (mm)	LEN (mm)	BE WIN (mm)	RES[1] (keV)	EFF[1] (%)	P/C[1]
1	N40071B	51.0	19.3	0.5	.62[2]	7[3]	-
2	-	-	-	0.5	-	20	-
3	N30228B	54.3	54.2	0.5	1.86	28.3	57.2:1
4	N20281	54.3	60.1	0.5	1.78	28.4	57.9:1
5	N30375	64.5	71.4	1.0[4]	2.06	56.9	67.9:1
6	N30201	64.5	85.4	0.5	2.20	62.9	62.4:1
7	N30410	69.1	64.4	0.5	2.09	64.2	67.1:1

Notes:
1. Measured using 1.33 MeV line, ^{60}Co.
2. Resolution at 122 keV, ^{57}Co.
3. Estimated efficiency.
4. Mg window.

TABLE 2. SUMMARY OF ^{137}Cs COMPTON SUPPRESSION PERFORMANCE

DET NO	UNSUPPRESSED			SUPPRESSED			IMPROVEMENT		
	P/C_p	P/C_e	P/T_A	P/C_p	P/C_e	P/T_A	P/C_p	P/C_e	P/C_A
1	71.1	58.2	0.12	312.8	336.5	0.24	4.40	5.78	2.00
2	109.1	88.8	0.18	695.8	758.1	0.36	6.38	8.54	2.00
3	121.2	98.4	0.21	795.2	864.9	0.43	6.56	8.79	2.05
4	122.4	97.8	0.20	758.1	791.9	0.40	6.19	8.10	2.00
5	140.5	112.9	0.27	884.5	839.5	0.51	6.30	7.44	1.89
6	131.0	102.7	0.27	880.6	940.9	0.48	6.72	9.16	1.78
7	158.7	-	-	895.5	-	-	5.64	-	-

Notes:

1. For P/C_p values, the plateau is measlured as the average counts per channel for the energy range 358 to 382 keV.
2. For P/C_e values, the edge is measured as the average counts per channel for the energy range 475 to 581 keV.
3. For P/C_A values, the total area is the sum of all conversions in the spectrum.
4. The conversion gain is 0.25 keV/Ch for all data.

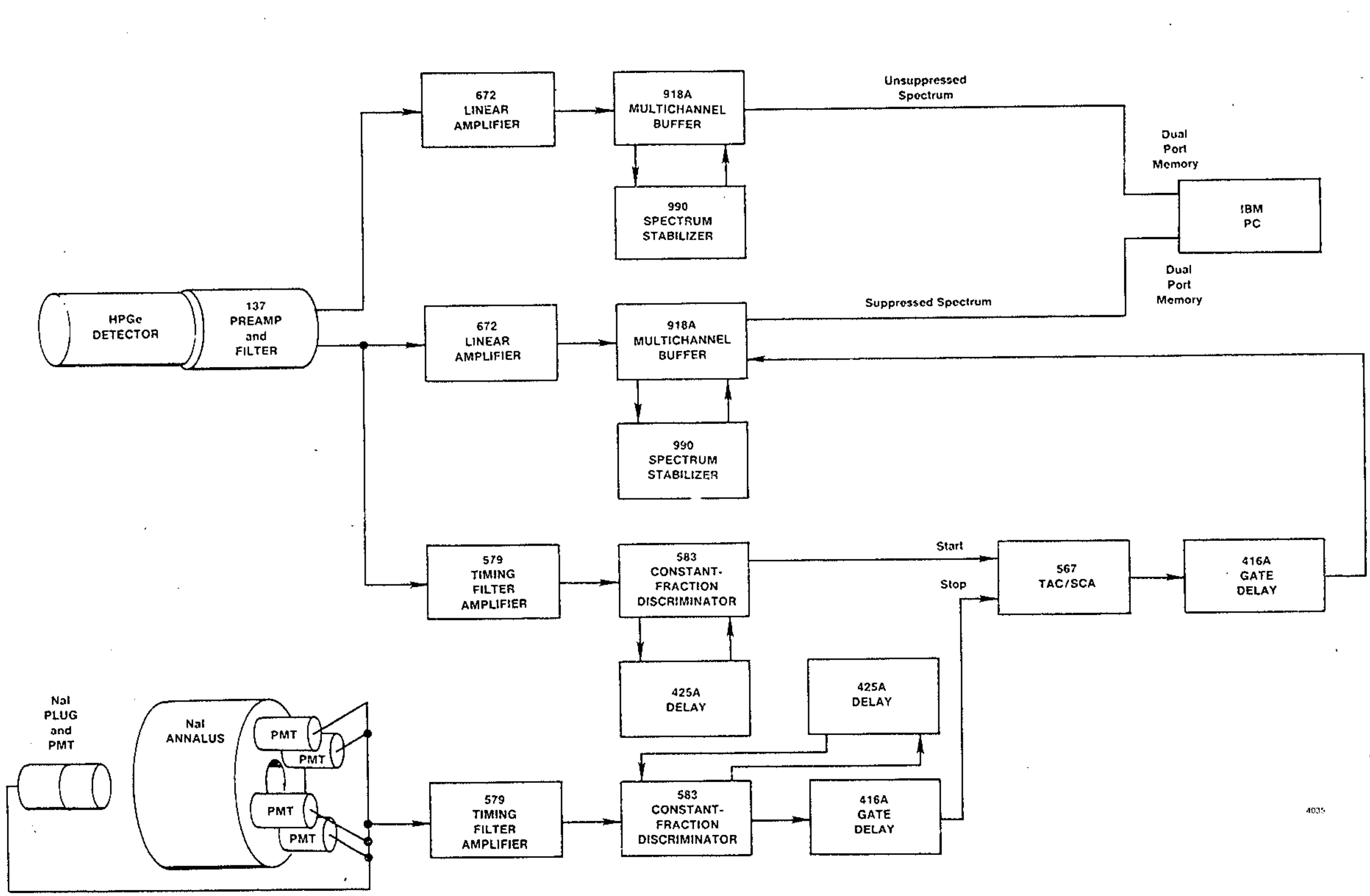

Fig. 1. Block Diagram of the Compton Suppression System.

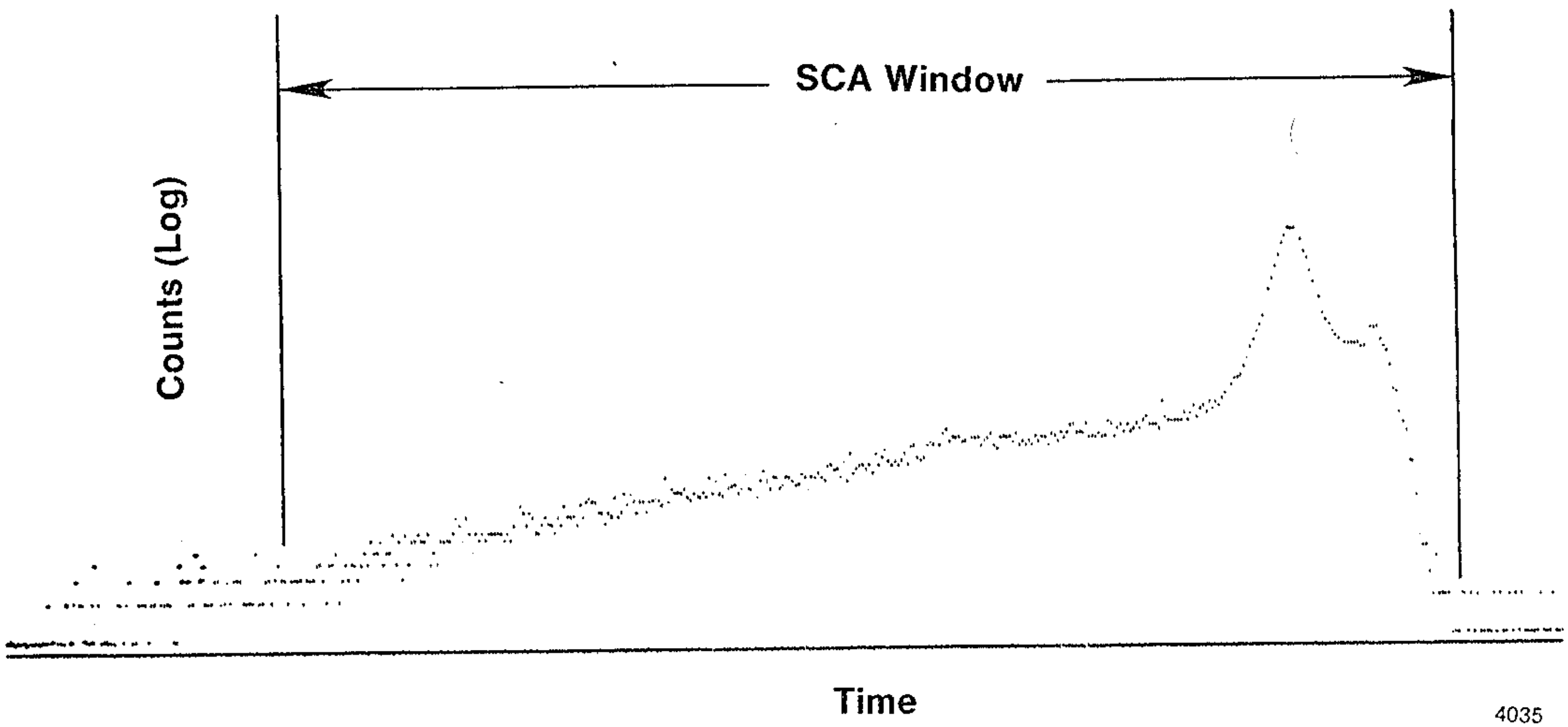

Fig. 2. Typical Timing Spectra for the Compton Suppression System.

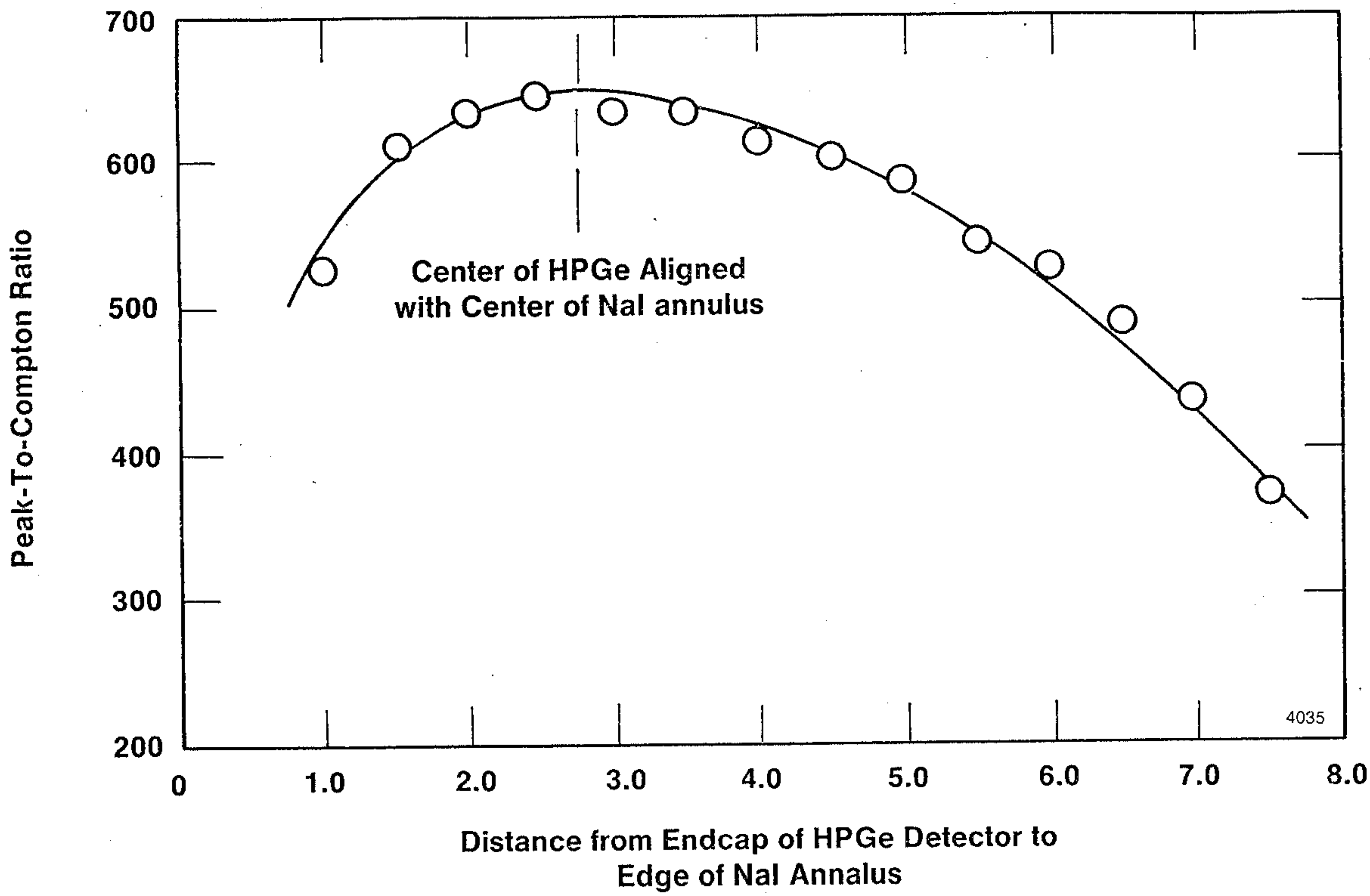

Fig. 3. Peak-to-Compton Ratio of the Suppressed System as a Function of the HPGe Detector Position in the NaI Annalus.

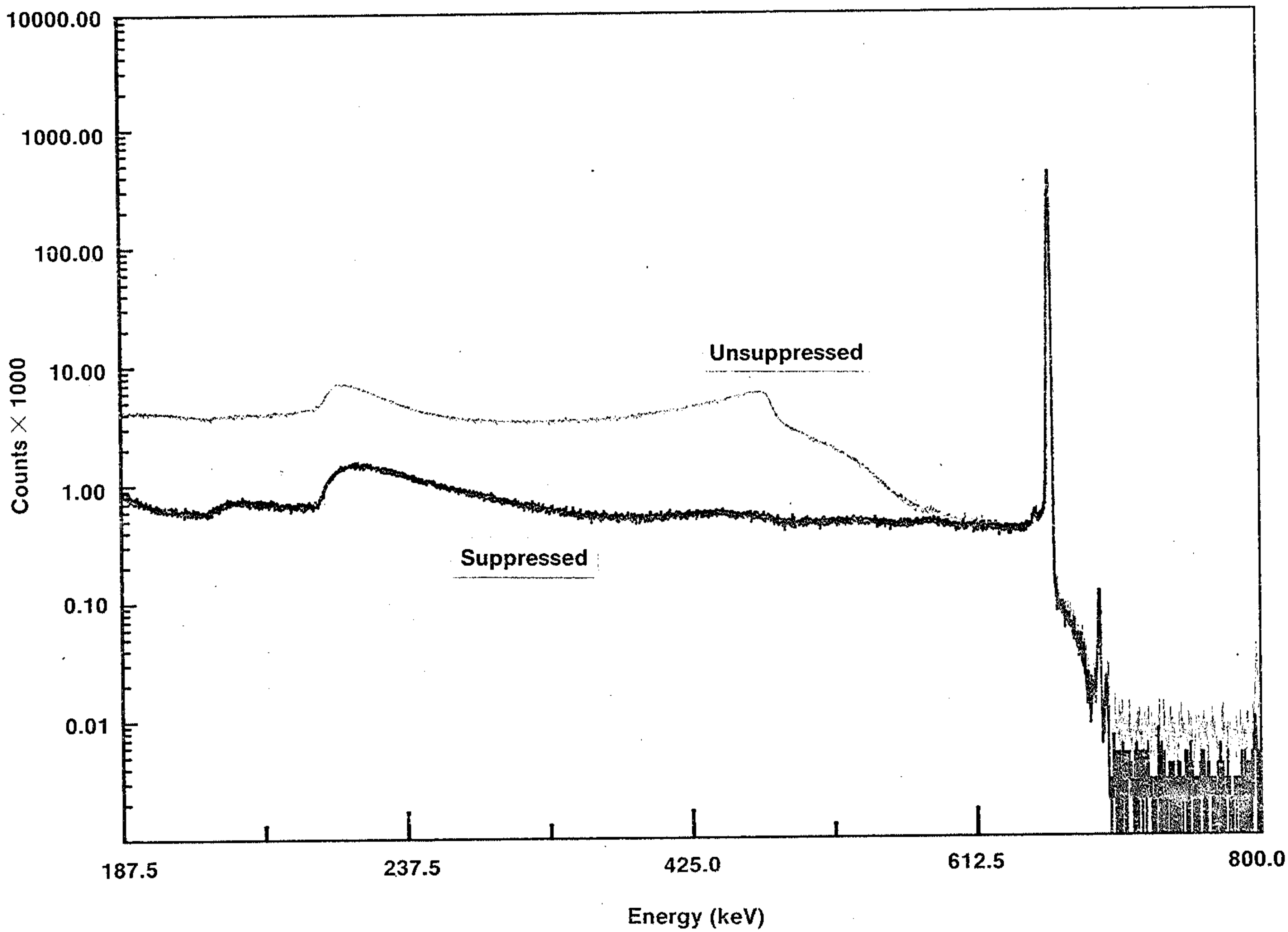

Fig. 4. Suppressed and Unsuppressed Spectra for 137Cs.

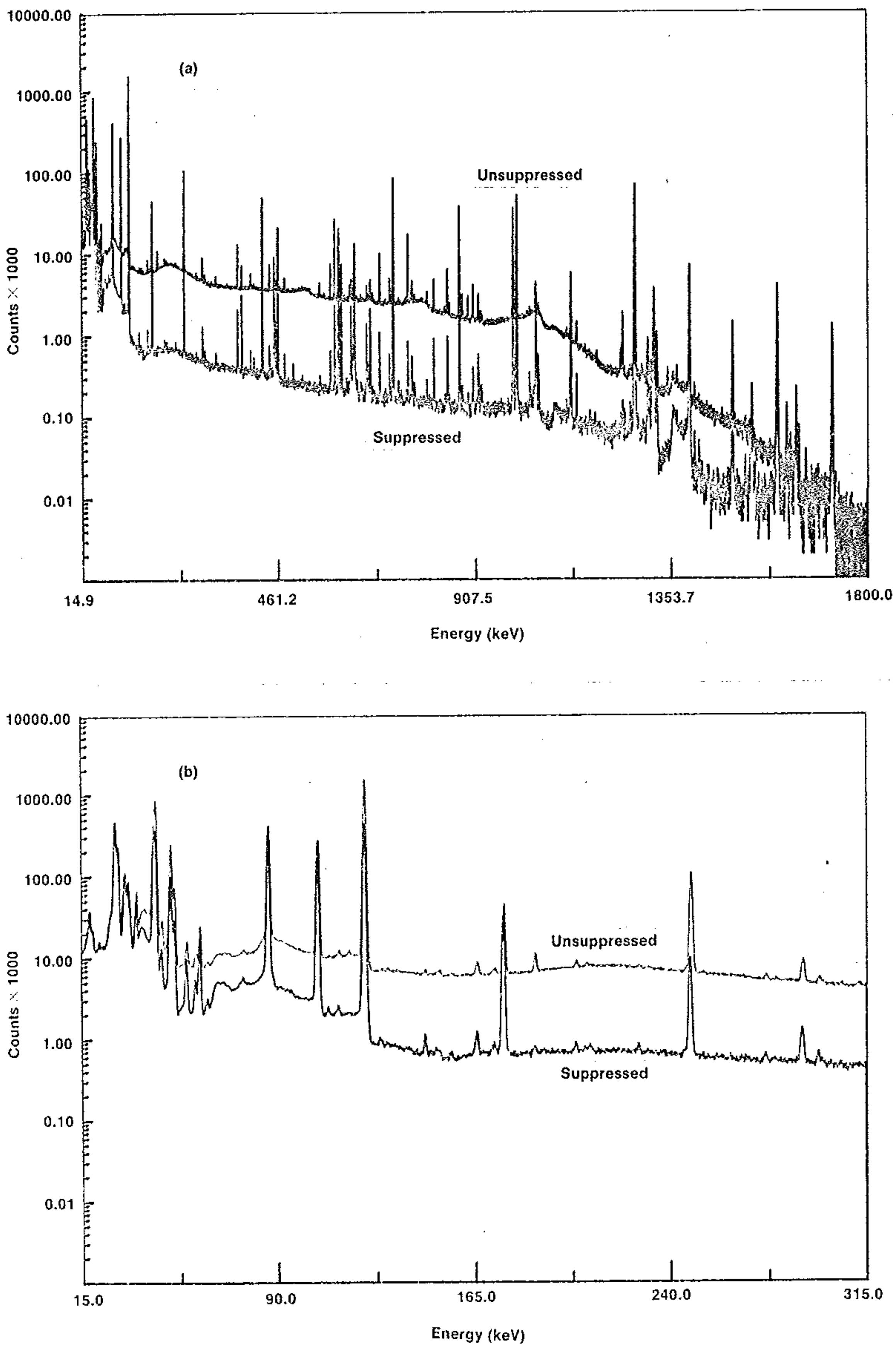

Fig. 5. Suppressed and Unsuppressed Spectra for ^{125}Sb-^{154}Eu-^{155}Eu Mixed Source (a) 15–1800 keV, and (b) 15–315 keV.

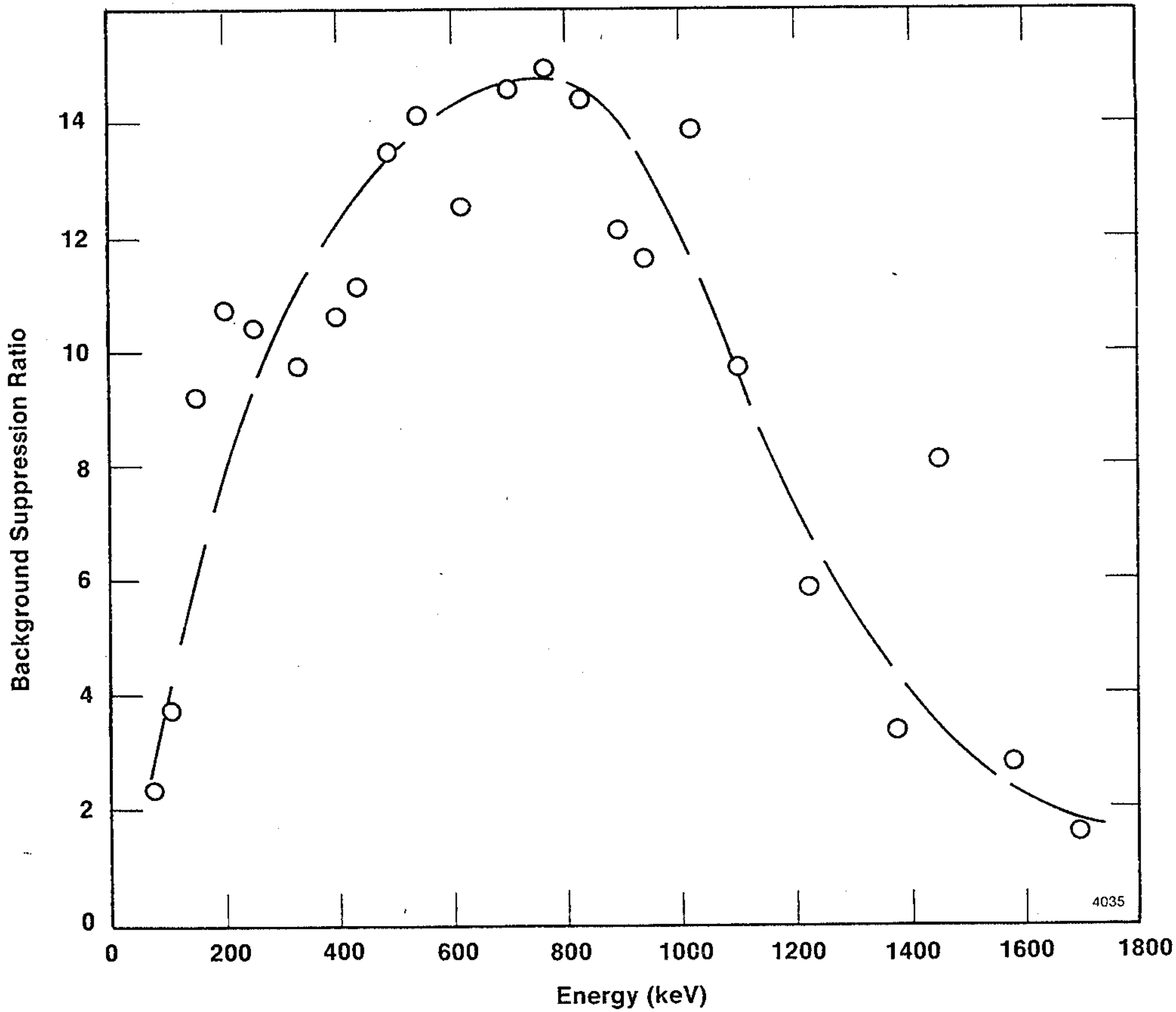

Fig. 6. Background Suppression Ratio as a Function of Energy.
(Conversion gain is 0.25 keV/Ch.)

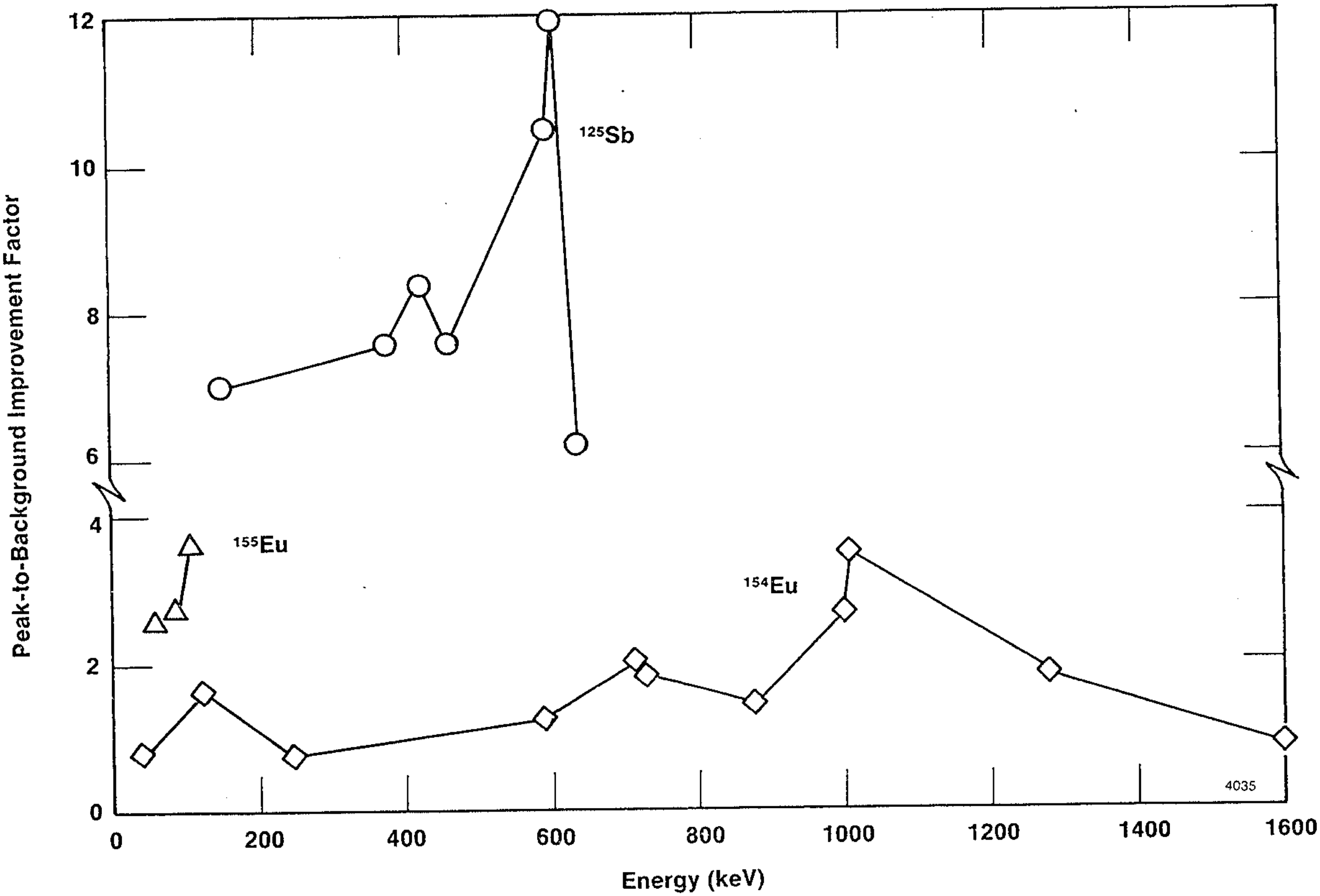

Fig. 7. Peak-to-Background Improvement Factor as a Function of Energy for Mixed ^{125}Sb-^{154}Eu-^{155}Eu Source. (Conversion gain is 0.25 keV/Ch.)

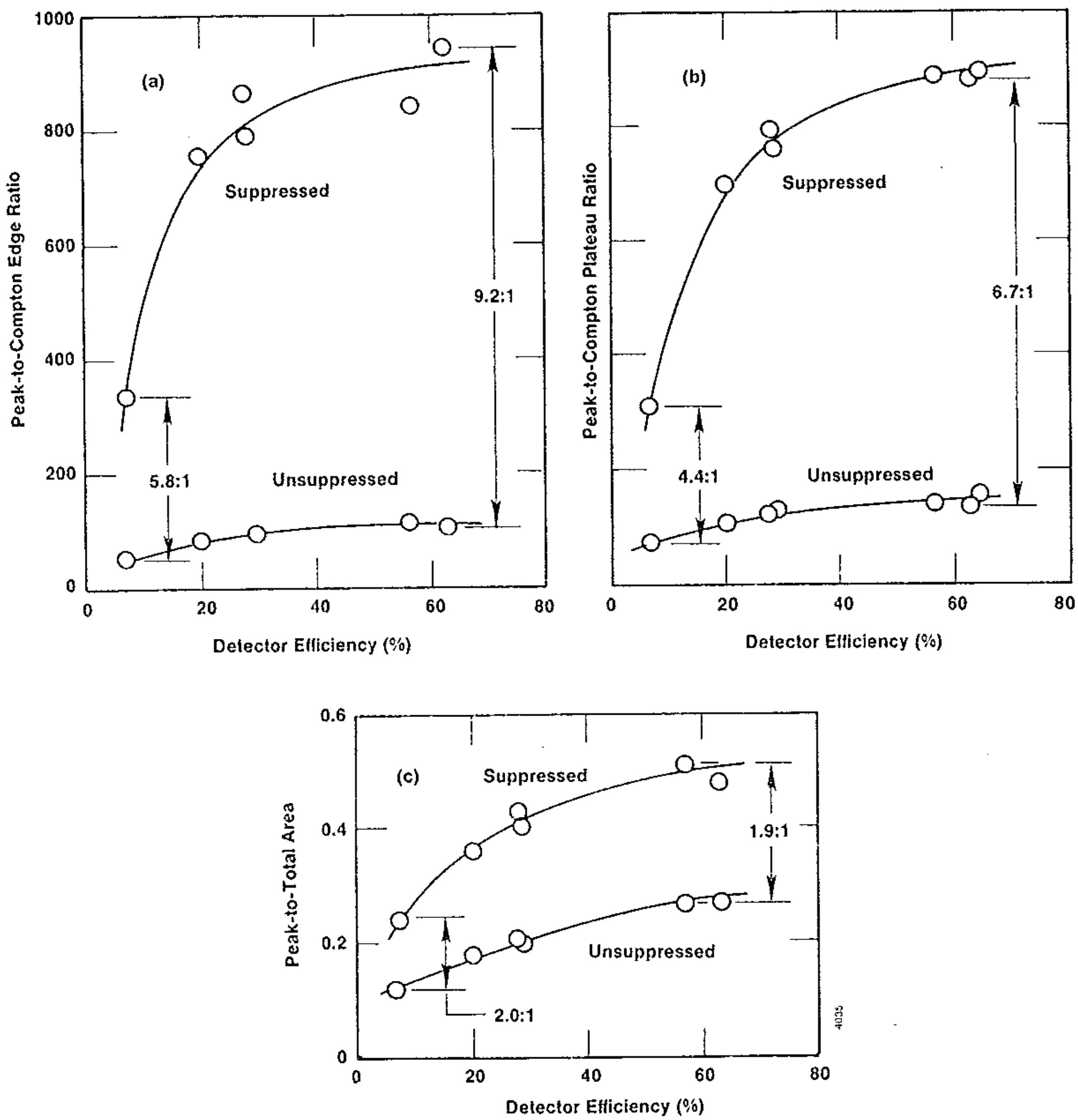

Fig. 8. Compton Suppression System Performance as a Function of HPGe Detector Efficiency: (a) Peak-to-Compton Edge (475–481 keV), (b) Peak-to-Compton Plateau (358–382 keV), and (c) Peak-to-Total Area.

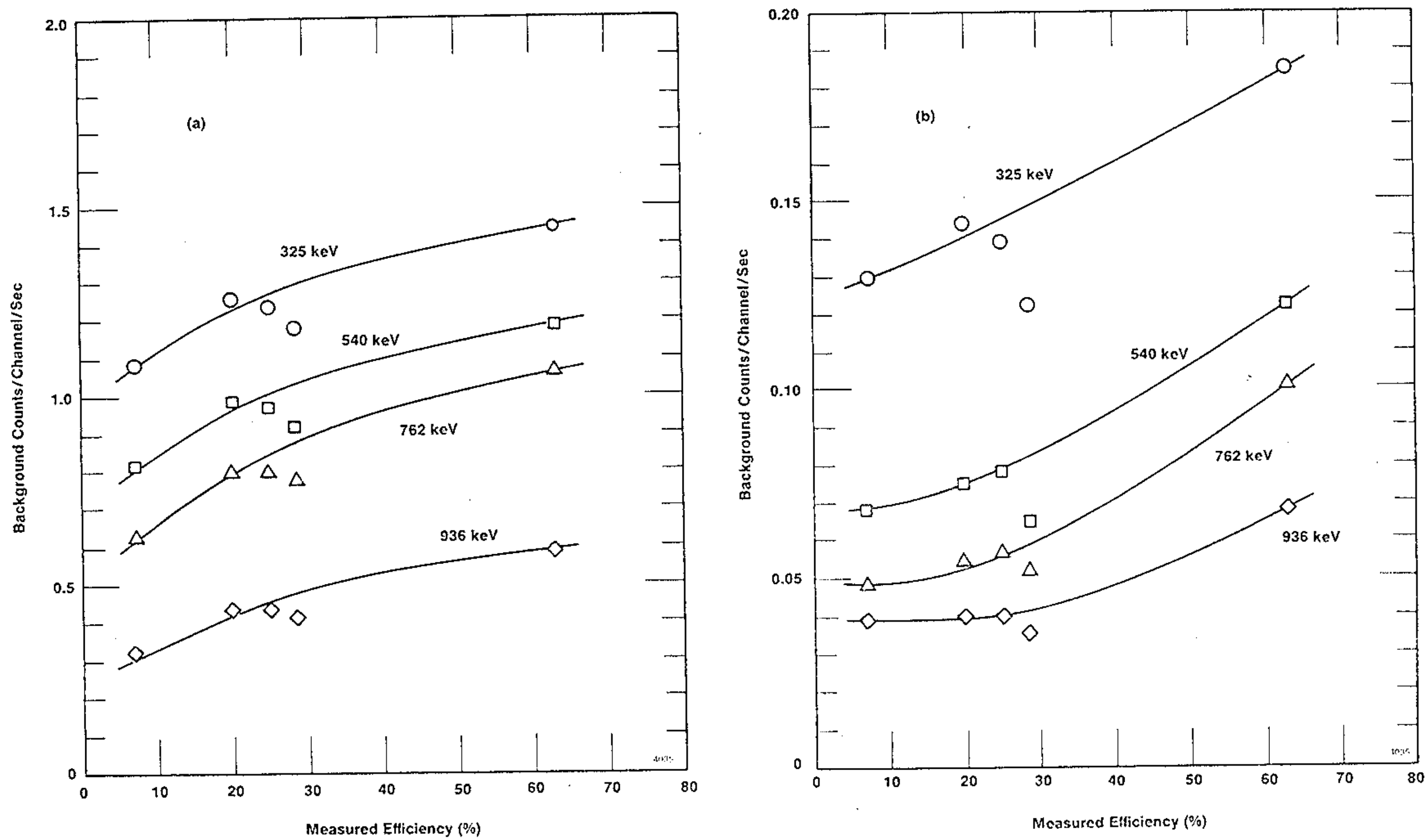

Fig. 9. Background Count-Rates in the Presence of a Mixed ^{125}Sb-^{154}Eu-^{155}Eu Source Vs. Detector Efficiency:
(a) Unsuppressed System, and (b) Suppressed System.
(Conversion gain is 0.25 keV/Ch.)

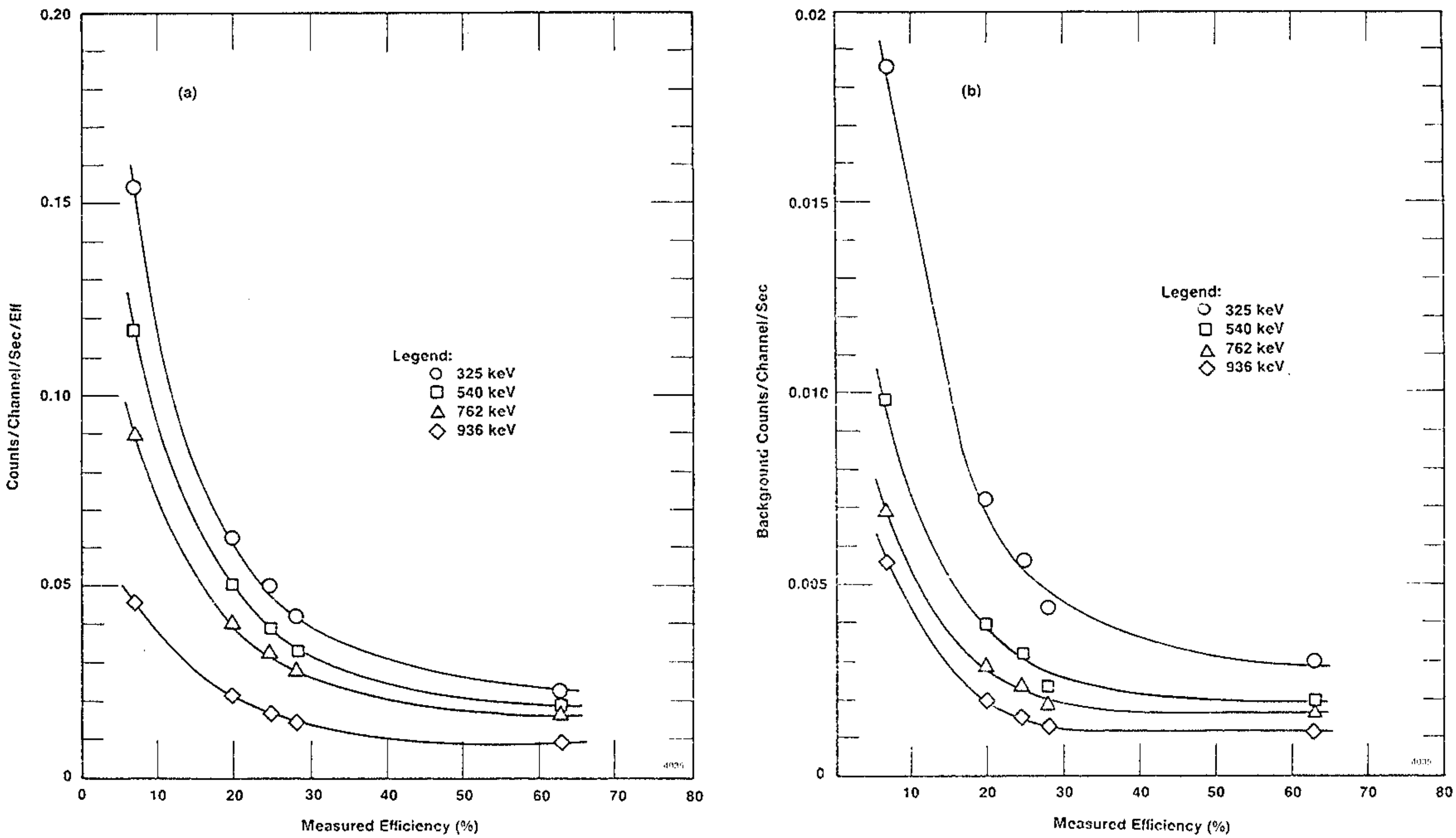

Fig. 10. Background Count-Rate per Percent of a Mixed ^{125}Sb-^{154}Eu-^{155}Eu Source Vs. Detector Efficiency:
(a) Unsuppressed System, and (b) Suppressed System.
(Conversion gain is 0.25 keV/Ch.)