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Ray Gold
BJ Kaiser
FS Moore
WL Bunch
WN McElroy
EM Sheen

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CONTINUOUS GAMMA-RAY SPECTROMETRY IN THE FAST FLUX TEST FACILITY (FFTF)†

Raymond Gold, Bruce J. Kaiser, Frank S. Moore, Jr.,
Wilbur L. Bunch, William N. McElroy, and Edwin M. Sheen

Westinghouse Hanford Company
Hanford Engineering Development Laboratory
Richland, Washington 99352, U.S.A.

ABSTRACT

Gamma-ray continua have been measured at startup in the Fast Flux Test Facility (FFTF). A special FFTF insert, called the In-Reactor Thimble (IRT), provided an adequate environment for in-situ operation of the gamma spectrometer. The IRT replaced a fuel assembly near core center (No. 2101) and measurements were conducted at three axial locations, namely midplane, the lower axial shield, and the upper axial reflector. Observations were carried out with Compton Recoil Gamma-Ray Spectrometry at the "state-of-the-art." Advantage was thereby taken of the most recent advances, including extension of gamma-ray spectrometry up to roughly 7 MeV with the new in-situ Janus detector probe. On this basis, in-core gamma-ray continua results are presented for FFTF.

INTRODUCTION

In reactor environments, the radiation field is comprised of two principal components, neutrons and gamma-rays. The history of reactor development reveals an initial concern for the neutron component of the radiation field that was virtually overriding. Such an initial emphasis is, of course, completely understandable. After all, fission reactors are neutron chain multiplying assemblies and only after a considerable amount of time were significant effects due to the gamma-ray component in reactor design, shielding, and safety actually recognized. Recognition of these effects has provided the impetus for improved characterization of reactor gamma-ray energy deposition and spectra. These general motivations have been summarized in a recent review of gamma-ray energy deposition and spectra in Fast Breeder Reactor (FBR) environments.[1]

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The fundamental entity underlying the description of the reactor gamma-ray component is the absolute gamma-ray energy spectrum. Radiation effects arising from the gamma-component are induced by the interaction of the absolute gamma-ray energy spectrum in the reactor environment. Consequently, accurate definition of this absolute spectrum is the goal of both theory and experiment. In light of these motivations, there now exist urgent and pragmatic needs for reactor benchmark gamma-ray spectrometry data. To this end, continuous gamma-ray spectrometry has been performed at startup in the Fast Flux Test Facility (FFTF).

FFTF, a 400 Mw fast reactor located on the Hanford reservation has been built by the U. S. Department of Energy (DOE) for irradiation testing and development of FBR fuels and materials. FFTF will provide the means to develop and operationally test FBR components and to gain operating experience for future FBR. Initial criticality was established on February 9, 1980.

IN-SITU ENVIRONMENT AND MEASUREMENT SEQUENCE

Gamma spectrometry was scheduled as part of a reactor characterization program for FFTF at startup, which consists of Very Low Power (VLP), Low Power (LP), and High Power (HP) irradiations.[2] In-core gamma-ray spectrometry was carried out at VLP in a specially designed FFTF insert called the In-Reactor Thimble (IRT). The IRT insert replaced a central fuel assembly (No. 2201) in the FFTF core for these VLP measurements and provided an adequate environment for the operation of spectrometry probes. In particular an ambient temperature of about 10°C was maintained at the interior of the IRT for these experiments, whereas the actual FFTF core temperature was approximately 200°C.

Actually continuous gamma-ray spectrometry was the very first IRT experiment and was carried out during February 24-29, 1980. Measurements were conducted at midplane, in the lower axial shield 81 centimeters below midplane, and in the upper axial reflector 64 centimeters above midplane. At each location background measurements were performed with the reactor completely shutdown, i.e., with all rods inserted. The choice of gamma spectrometry as the very first experiment in the IRT was based on the need to keep the background gamma intensity at the lowest possible level. This background intensity together with the finite response time of pulse processing instrumentation combine to create an effective limitation for in-core gamma-ray spectrometry. Even so, the plutonium fueled FFTF (core No. 1) produced a total background event rate of roughly $1.3 \cdot 10^4$ counts/sec at the midplane location.

Following background observations at each location, measurements were sequentially carried out at two different (subcritical) power levels in order to focus on complementary regions of the gamma spectrum. The gamma-ray energy region below roughly 4 MeV was emphasized in the lower power level irradiation, whereas the upper power level was used for the gamma-ray energy region above 4 MeV. Measurements were conducted for at least four hour durations at each power level so that some data could be obtained on the approach to equilibrium due to the buildup of fission product gammas.

EXPERIMENTAL SPECTROMETRY METHOD

For these FFTF measurements, Compton Recoil Gamma-Ray Spectrometry was used. In such reactor environments, gamma-ray spectra are continuous and the absolute magnitude as well as the general shape of the gamma continuum are of paramount importance. Consequently, conventional methods of gamma-ray detection are not suitable for in-core gamma-ray spectrometry. To meet these specific needs, a method of continuous gamma-ray spectrometry, namely Compton Recoil Gamma-Ray Spectrometry, was developed for in-situ observations in reactor environments.[3-5] In addition to applications in reactor science,[6-9] it has been used to measure gamma continua which arise in such applied disciplines as shielding, dosimetry,[10] health physics,[11] radiobiology and environmental science.[12,13] The "state-of-the-art" of this method has been recently summarized with special emphasis on improvements for in-core reactor gamma-ray spectrometry.[14,15]

In spite of these advances, Compton Recoil Gamma-Ray Spectrometry still possesses a number of important limitations. From the viewpoint of in-core reactor spectrometry, perhaps the most fundamental restriction is the high energy limit available with this method. Electron escape from the finite sensitive volume of the detector creates this limitation. Solid-state lithium-drifted silicon Si(Li) detectors are used for in-core gamma spectrometry. Since these detectors are not very large, typically $\sim 1\,\mathrm{cm}^3$ in volume, higher energy electrons readily escape from (or enter into) the sensitive region. Obviously, the probability of electron escape (or entry) increases with increasing electron energy.

Electrons which escape from (or enter into) these Si(Li) detectors generally interact in the transition region between the sensitive and dead regions of the solid-state detector. Interactions in this semi-sensitive region produce pulses of much slower rise-time. Hence using pulse rise-time measurements, one can detect such defective events. However, despite the application of these pulse-shape techniques to detect electron escape (or entry), a 1 cm^3 Si(Li) detector possesses an upper limit for accurate gamma spectrometry of only about 2 MeV or so. Since gamma-rays in reactor environments can be far in excess of 2 MeV, extension of this high energy limitation is essential.

Work towards this end has gone forward.[14,15] As a result of these efforts, a new gamma-ray detection system has been developed which extends the applicability of Compton Recoil Gamma-Ray Spectrometry up to roughly 7 MeV. This detection system is comprised of two separate Si(Li) detectors placed face-to-face, as shown in Figure 1. Hence this new detection system is called the Janus probe. Also shown in Figure 1 is the block diagram of pulse processing instrumentation for the Janus probe. This new gamma probe not only extends the upper energy limit of in-core gamma-ray spectrometry, but in addition possesses the following fundamental advantages:

(1) A completely contained sensitive region for application of pulse-shape discrimination, as opposed to a single detector which normally possesses at least one non-contained face.

(2) Two complementary modes of operation (see Figure 1):
   (a) The non-coincidence mode for low energy spectrometry ($\lesssim$4 MeV).
   (b) The coincidence mode for high energy spectrometry ($\gtrsim$4 MeV).

(3) Improved discrimination against neutron induced events, since neutron interactions produce short range events which are excluded in the coincidence-mode operation.

(4) Improved high energy coincidence mode response for unfolding analyses.

(5) Improved pulse shape discrimination in the high energy-coincidence mode, through significant peaking of rise time spectra.

The elementary response of the Janus probe to monoenergetic gamma-rays was determined principally with radioisotopic sources. However, to extend response function measurements to higher energy, monoenergetic sources were obtained using the ^{9}Be(α,n)^{12}C* and ^{19}F(p,α)^{16}O* reactions at a Van de Graaff accelerator. Table I contains those monoenergetic gamma-ray sources used in the present response function measurements, listed in order of increasing gamma-ray energy. Response observations were carried out as a function of the gamma-ray angle of incidence, Θ, from normal incidence to the Janus probe detector faces (0°) to backward incidence (180°), in 45° intervals.

TABLE I

Gamma-Ray Calibration Sources

Radioisotope	Photon Energy (MeV)	Compton Edge Energy (MeV)
^{198}Au	0.412	0.2543
^{64}Cu	0.5110	0.3407
^{137}Cs	0.6616	0.4773
^{65}Zn	1.115	0.9071
^{52}V	1.434	1.217
^{28}Al	1.780	1.557
^{24}Na	2.754	2.520
	1.369	1.154
^{12}C^{a}	4.439	4.197
^{16}O^{b}	6.130	5.885

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[a] Obtained from the ^{9}Be(α,n)^{12}C* reaction.

[b] Obtained from the ^{19}F(p,α)^{16}O* reaction.

Janus probe signals are analyzed in a two parameter mode (see Figure 1) to provide both the energy spectrum as well as the rise time spectrum (RTS). Figure 2 presents Janus probe RTS obtained in the non-coincidence and coincidence modes with monoenergetic gamma-rays from ^{24}Na. The increased peaking of the coincidence mode RTS affords improved pulse shape discrimination against defective events at higher electron energy.

The sensitivity of these RTS observations enables one to measure the finite-size retention probability of recoil electrons in these Si(Li) detectors. The retention probability, P, of electrons in the finite sensitive volume of a detector depends on a number of variables. In general, P depends upon the gamma-ray energy ε_0, the recoil electron energy, E, and the angle of incidence of the gamma-ray Θ. Hence the retention probability is generally denoted by $P(\varepsilon_0, E, \Theta)$.

Heretofore RTS measurements of such sensitivity could not be carried out, thus necessitating certain simplifying assumptions in the unfolding analysis of observed electron spectra.[3-5] In particular, it was assumed that P was independent of both ε_0 and Θ. With the present capabilities of observing RTS, one no longer need rely on such assumptions and more accurate data analysis can thereby be performed. On the other hand, these very capabilities permit investigation of the validity of these earlier assumptions.

To illustrate the high electron energy response of the Janus probe, Figure 3 displays the coincidence mode response due to 4.44 gamma-rays. The response in Figure 3 due to 4.44 MeV gamma-rays has been obtained using the $^9Be(\alpha,n)^{12}C^*$ reaction together with an intense source of ^{54}Mn-0.835 MeV gamma-rays to simulate the effect of low energy gammas, as would exist in a typical reactor environment. Comparisons carried out with and without this intense ^{54}Mn source have established that low energy gamma-rays have completely negligible effect upon the high electron energy Janus response, even for total event rates approaching 10^5 counts/sec.

Electron energy response due to monoenergetic 6.13 MeV gamma-rays are presented in Figure 4 for both the coincidence and non-coincidence modes. In contrast with the non-coincidence response, the slowly varying nearly constant behavior of the coincidence mode provides a better "conditioned" response matrix for subsequent unfolding analyses.

An interesting effect arises in the response of these Si(Li) detectors at higher energy, as illustrated in Figures 3 and 4. While the Compton interaction still dominates, a distinct double-escape peak from pair production is clearly observable. For 4.44 MeV gamma-rays, the double-escape peak falls at approximately 3.4 MeV, whereas the Compton edge occurs at approximately 4.2 MeV. For 6.13 MeV gamma-rays, the double escape peak falls at approximately 5.2 MeV, whereas the Compton edge occurs at approximately 5.9 MeV. Since pair-production increases with increasing gamma-ray energy, this effect must obviously be accounted for in high energy gamma-ray spectrometry. Otherwise spurious peaks could be introduced in the gamma continuum through the unfolding analysis of the observed electron spectrum.

SPECTROMETRY RESULTS

On the basis of these response function measurements, gamma-ray continua can be obtained from an unfolding analysis of observed electron spectra. Work is now in progress toward the construction of a response matrix for the Janus probe on entirely empirical grounds. However, these efforts have not been completed to date. Consequently, to obtain preliminary FFTF gamma spectra, data reduction and unfolding analysis was carried out with codes developed some time ago.[16]

FFTF gamma-ray spectra so obtained are presented together with the corresponding electron energy distributions in Figures 5, 6, and 7 for midplane, the lower axial shield, and the upper axial reflector, respectively. Since the codes utilized in these data reductions do not actually represent the Janus probe response and effects such as pair production are not treated, experimental error cannot possibly be assigned. Hence the presented spectral data can only be regarded as qualitative.

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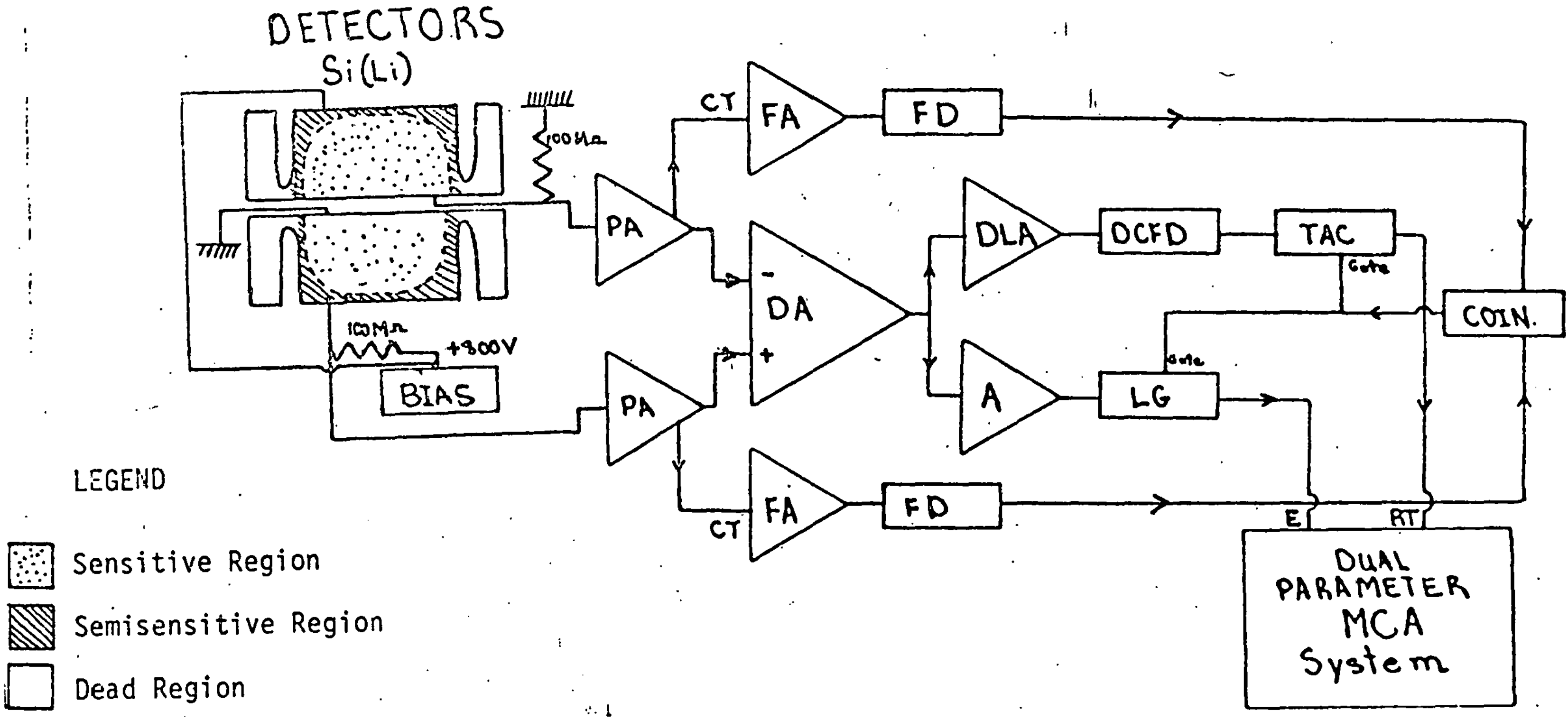

PA = Preamplifier
DA = Differential Amplifier
FA = Fast (nanosec) Amplifier
A = Linear Amplifier
DLA = Delay Line Amplifier
FD = Fast (100 MHz) Discriminator
DCFD = Dual Constant Fraction Discriminator
COIN = Fast Coincidence Network
LG = Linear Gate
TAC = Time to Amplitude Converter

E = Energy Pulse
RT = Rise Time Pulse
CT = Coincidence Timing Pulse

FIGURE 1. Cross Sectional View of Janus Detector Configuration and Block Diagram of Pulse Processing Instrumentation.

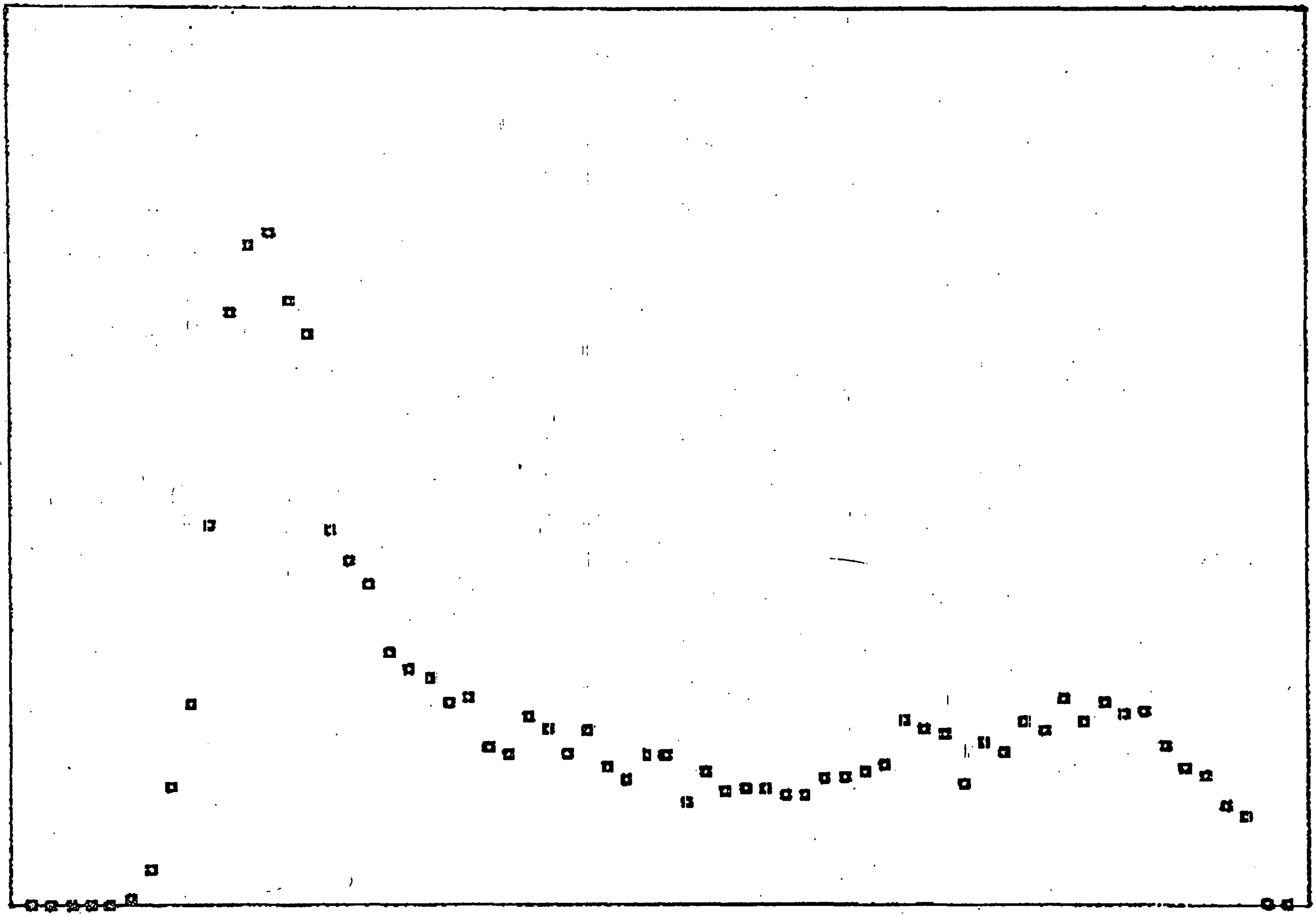

FIGURE 2a. Rise Time Spectrum Taken With the JANUS Probe in the Non-Coincidence Mode Utilizing 2.754 MeV Gamma-Rays.

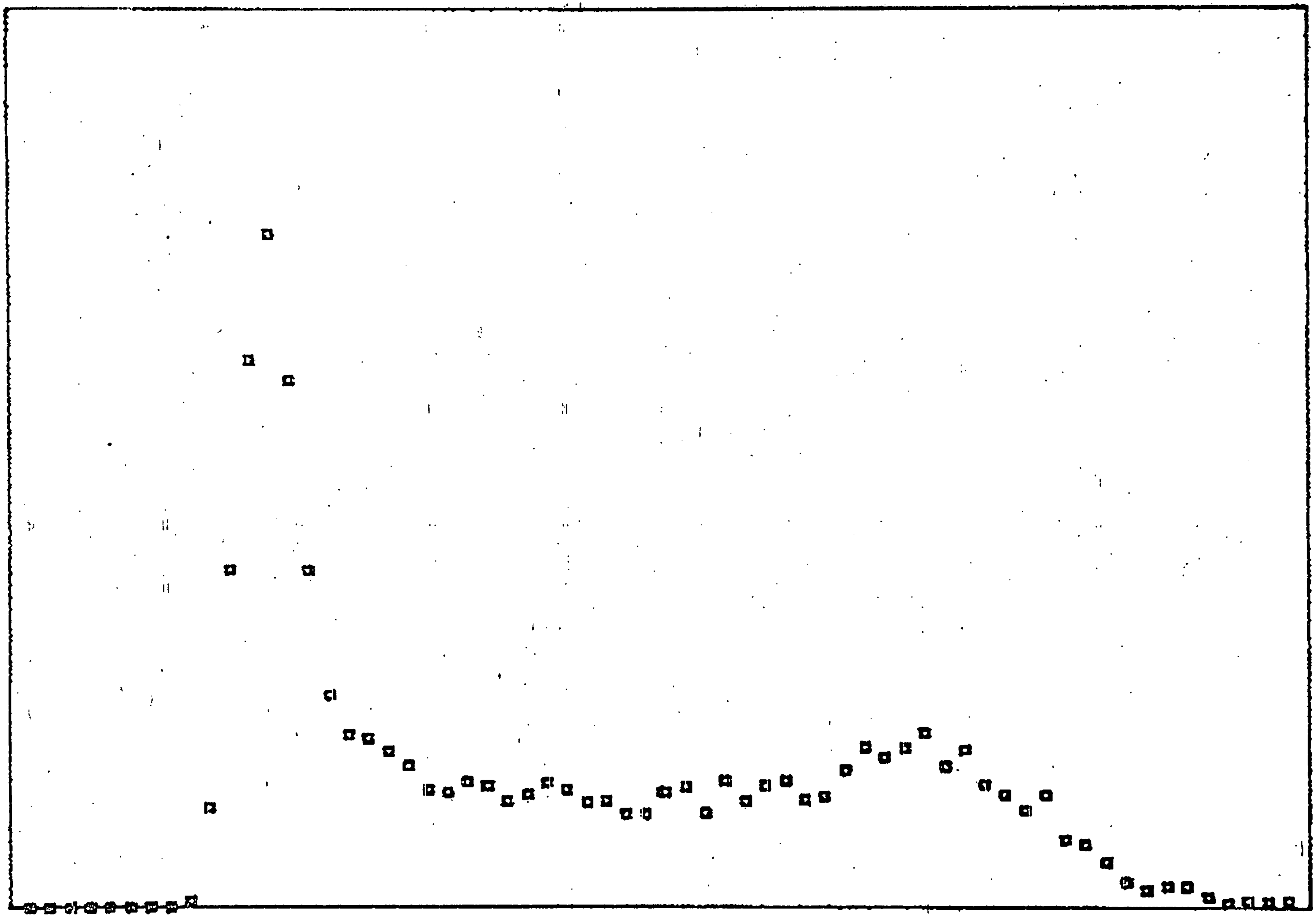

FIGURE 2b. Rise Time Spectrum Taken With the JANUS Probe in the Coincidence Mode Utilizing 2.754 MeV Gamma-Rays.

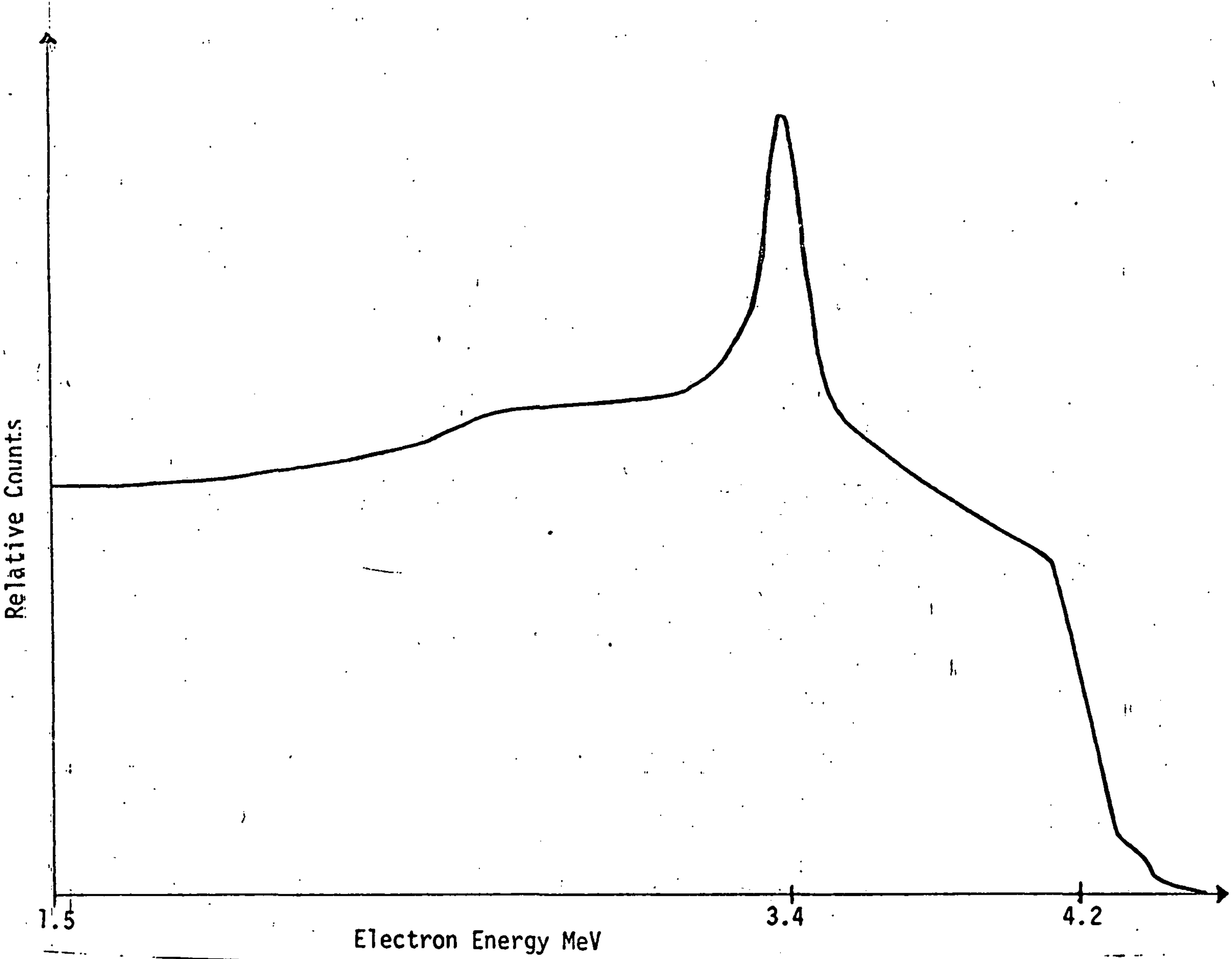

FIGURE 3. Coincidence Response Mode of the Janus Detection System to 4.44 MeV Gamma-Rays.

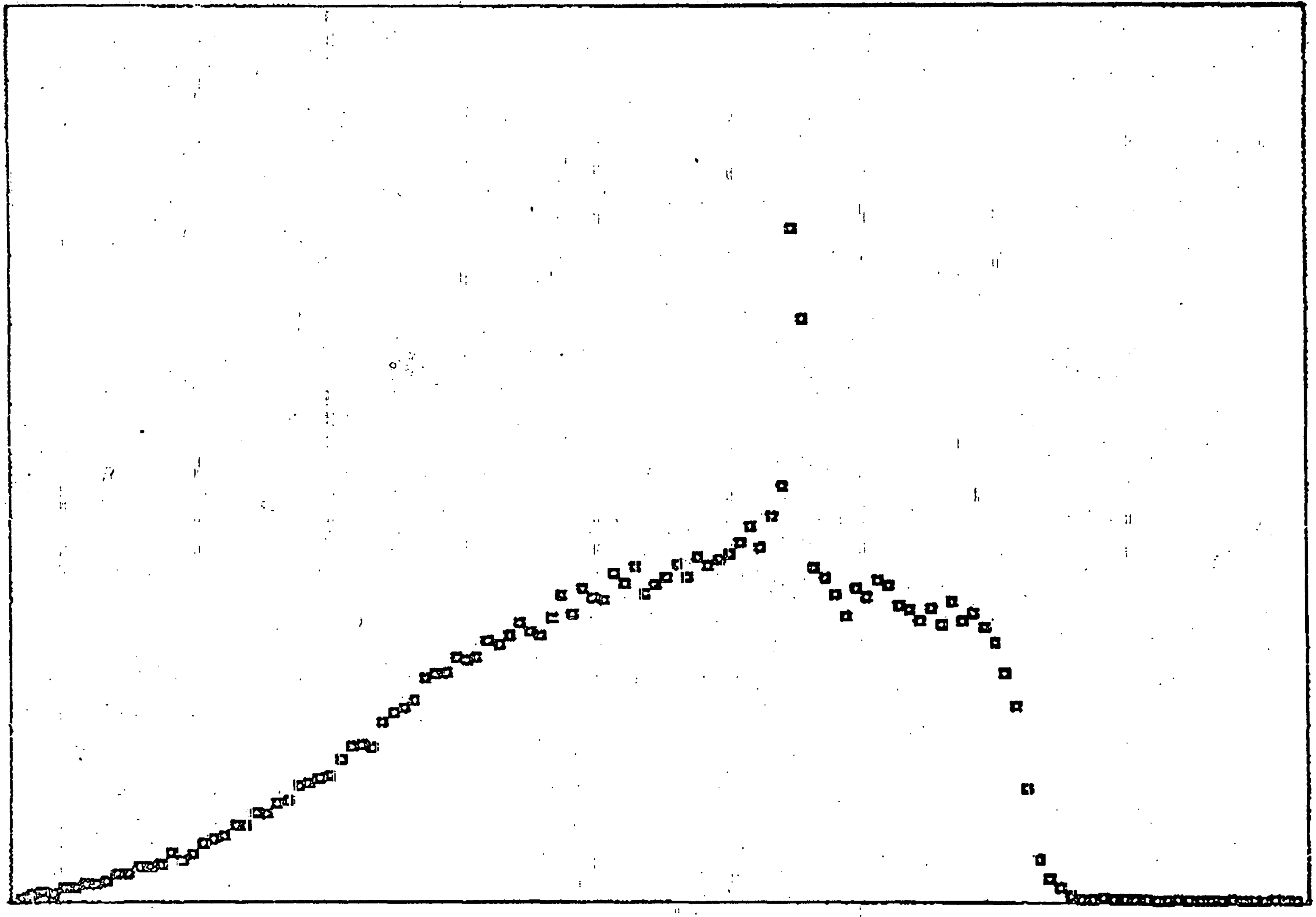

FIGURE 4a. Electron Energy Response for 6.13 MeV Gamma-Rays Taken With the JANUS Probe in the Coincidence Mode.

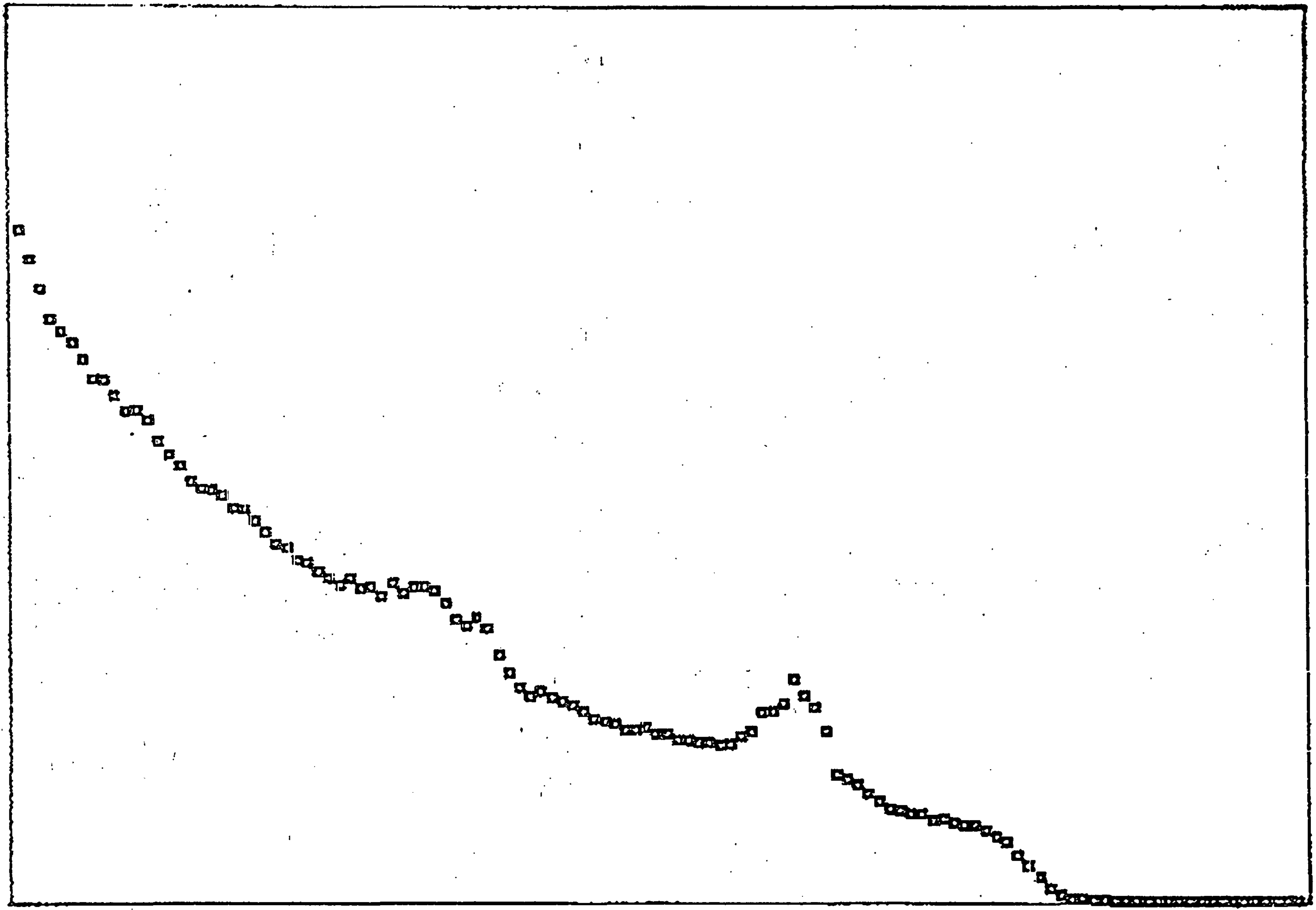

FIGURE 4b. Electron Energy Response for 6.13 MeV Gamma-Rays Taken With the JANUS Probe in the Non-Coincidence Mode.

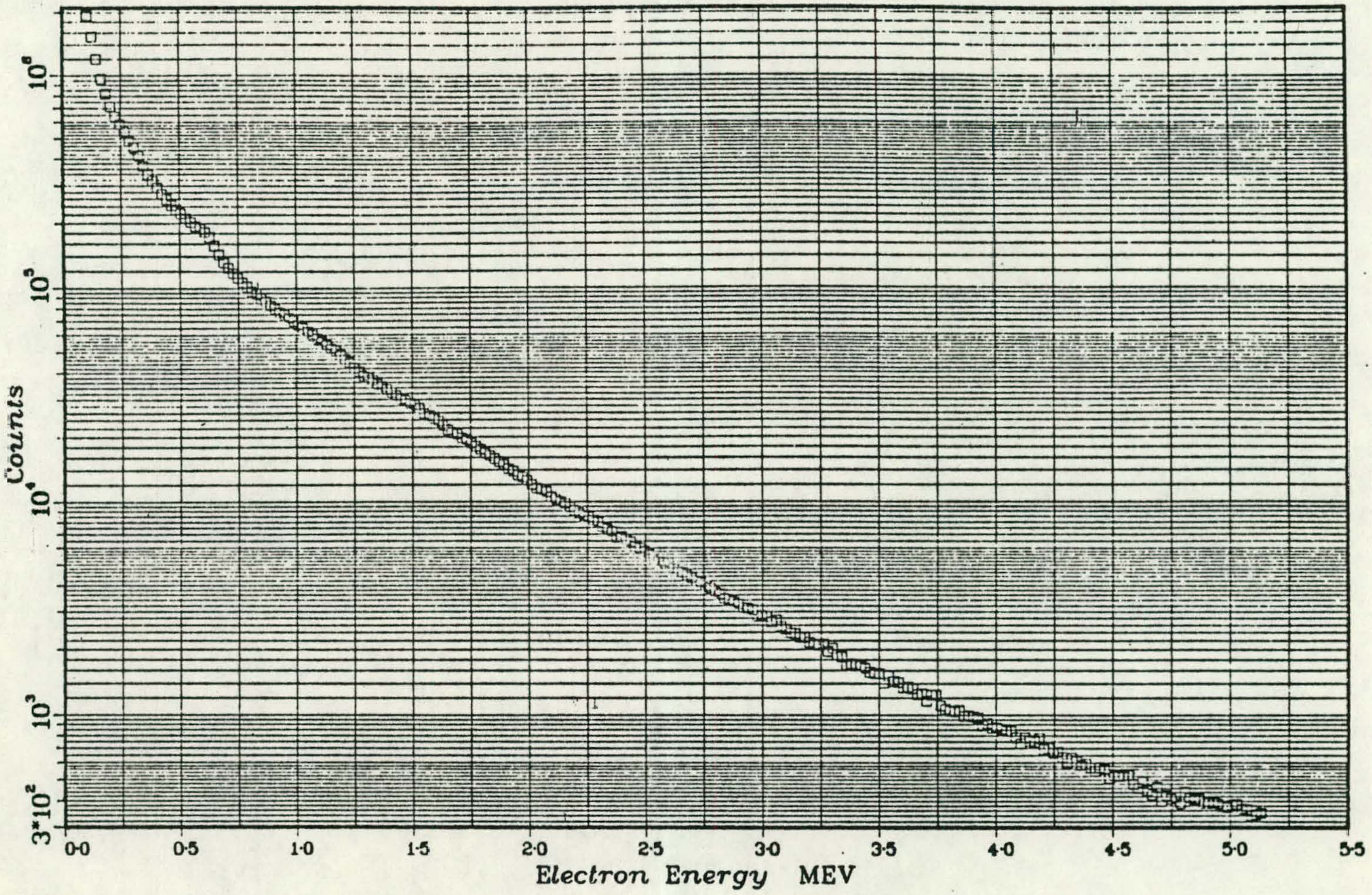

FIGURE 5a. Background Subtracted Low Energy Electron Spectrum Obtained With the Janus Probe (Non-Coincidence Mode) at FFTF Core Midplane in the Lower Power Level Irradiation.

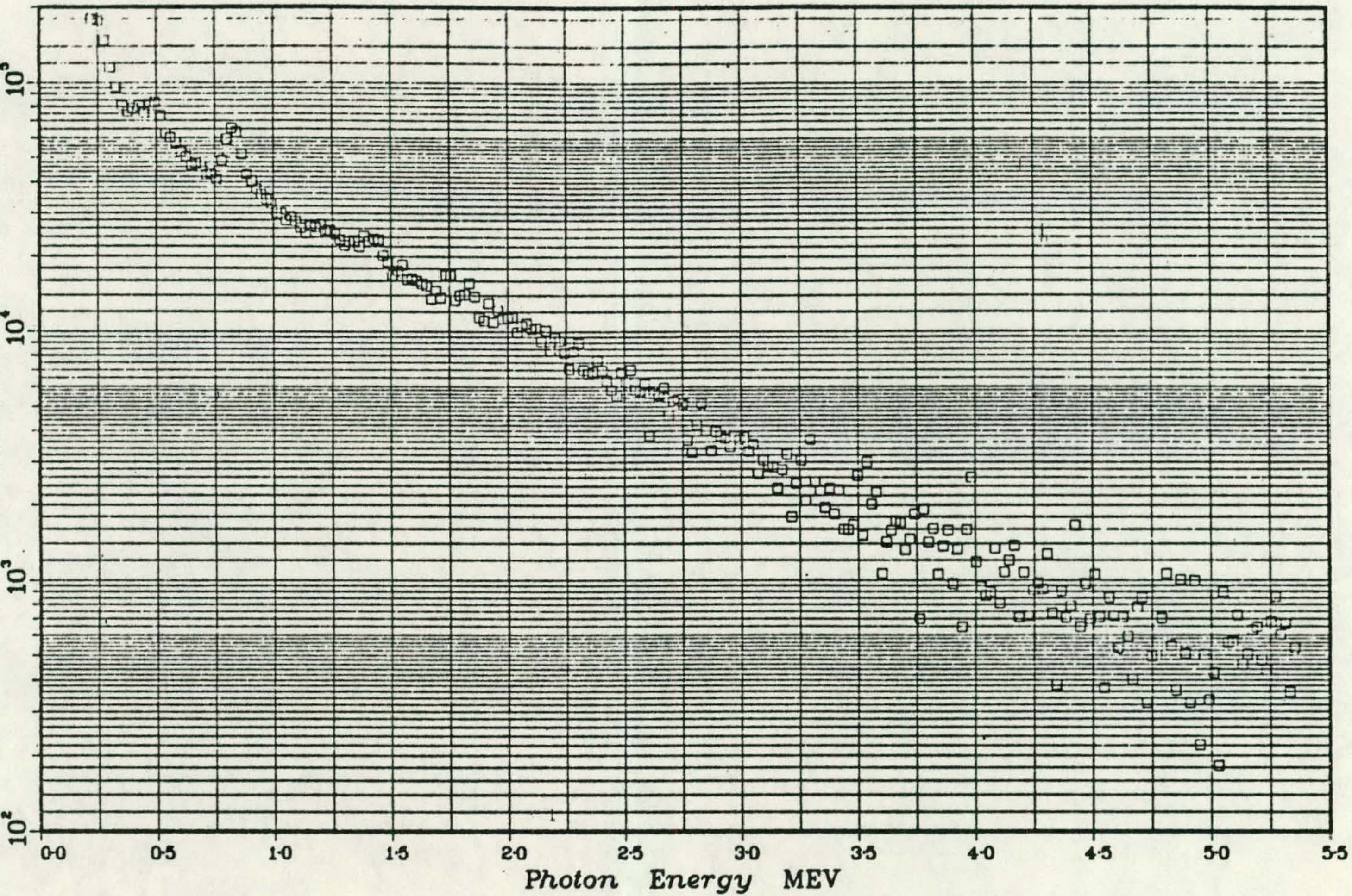

FIGURE 5b. Unfolded Gamma-Ray Continuum Attained at FFTF Core Midplane in the Lower Power Level Irradiation.

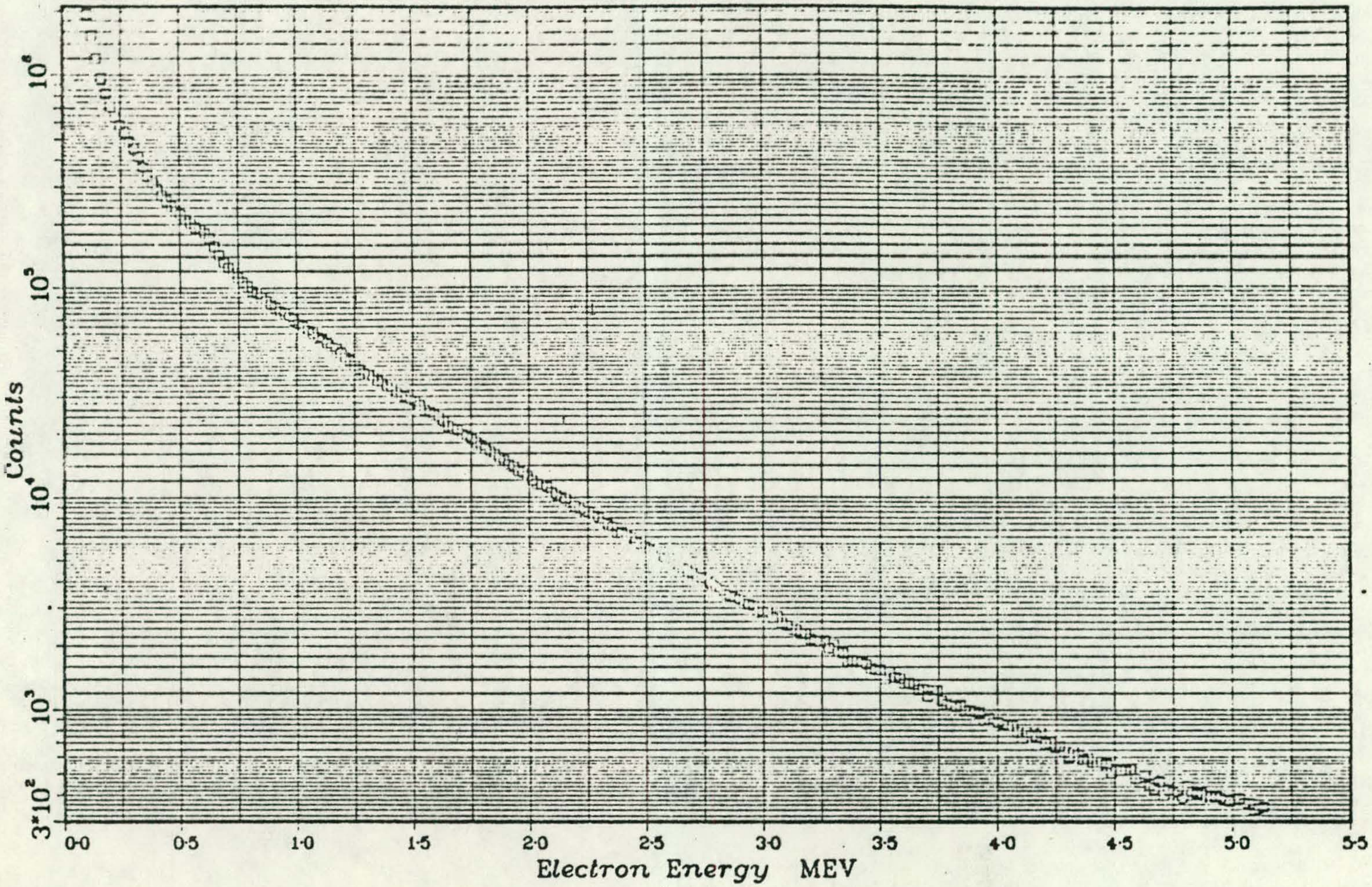

FIGURE 6a. Background Subtracted Low Energy Electron Spectrum Obtained With the Janus Probe (Non-Coincidence Mode) at FFTF Lower Axial Shield in the Lower Power Level Irradiation.

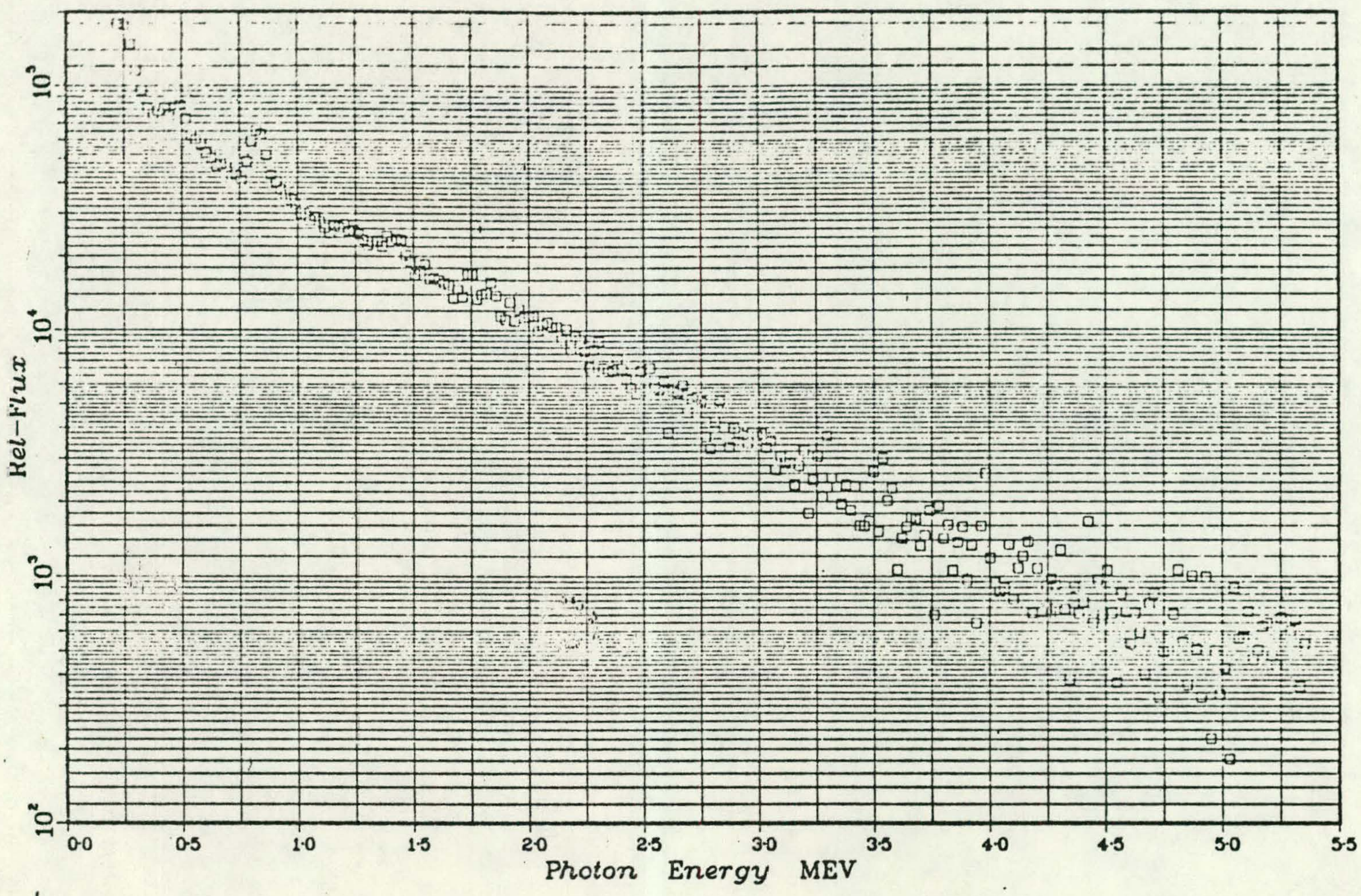

FIGURE 6b. Unfolded Gamma-Ray Continuum Attained at FFTF Lower Axial Shield in the Lower Power Level Irradiation.

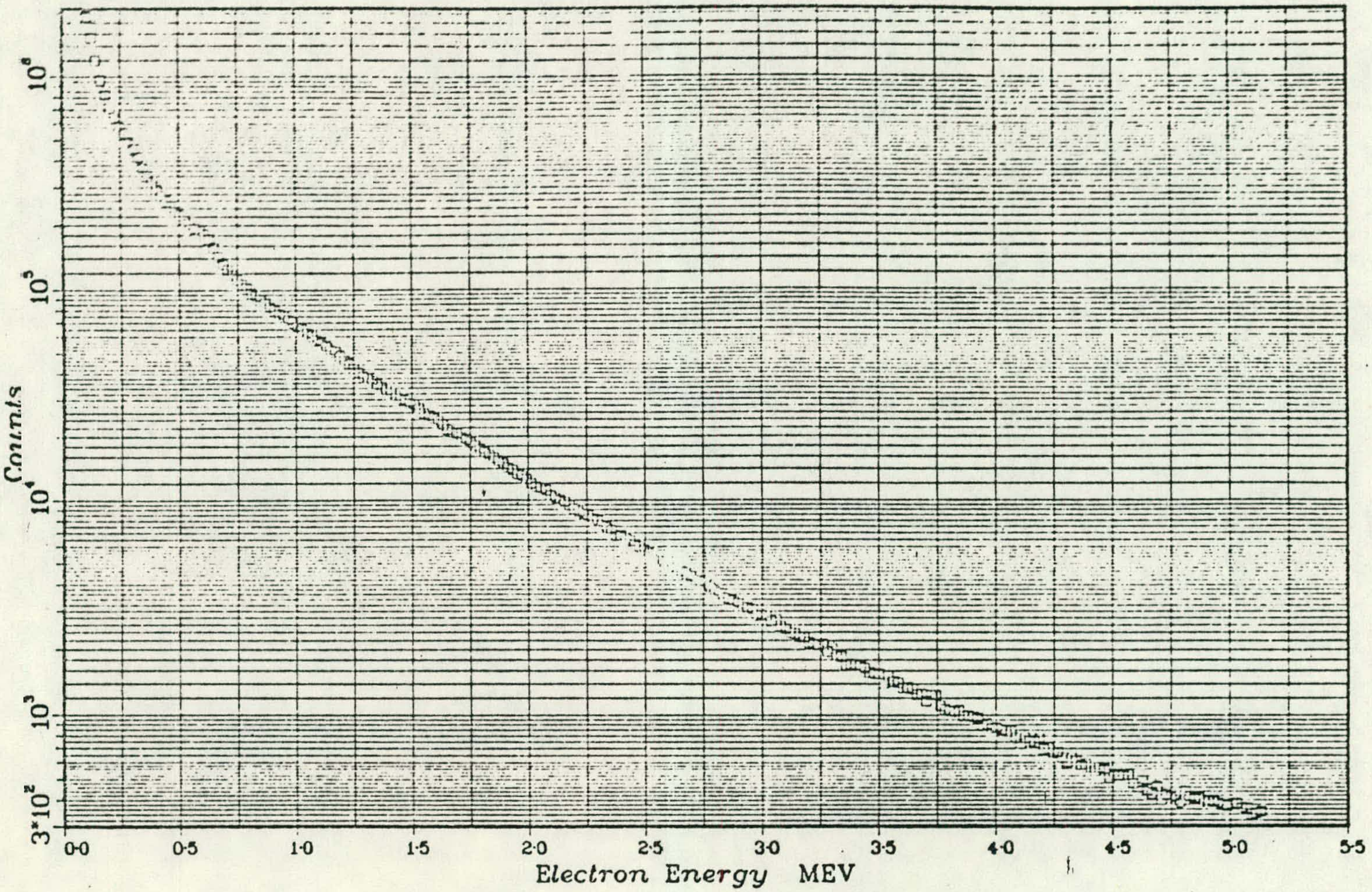

FIGURE 7a. Background Subtracted Low Energy Electron Spectrum Obtained With the Janus Probe (Non-Coincidence Mode) at FFTF Upper Axial Reflector in the Lower Power Level Irradiation.

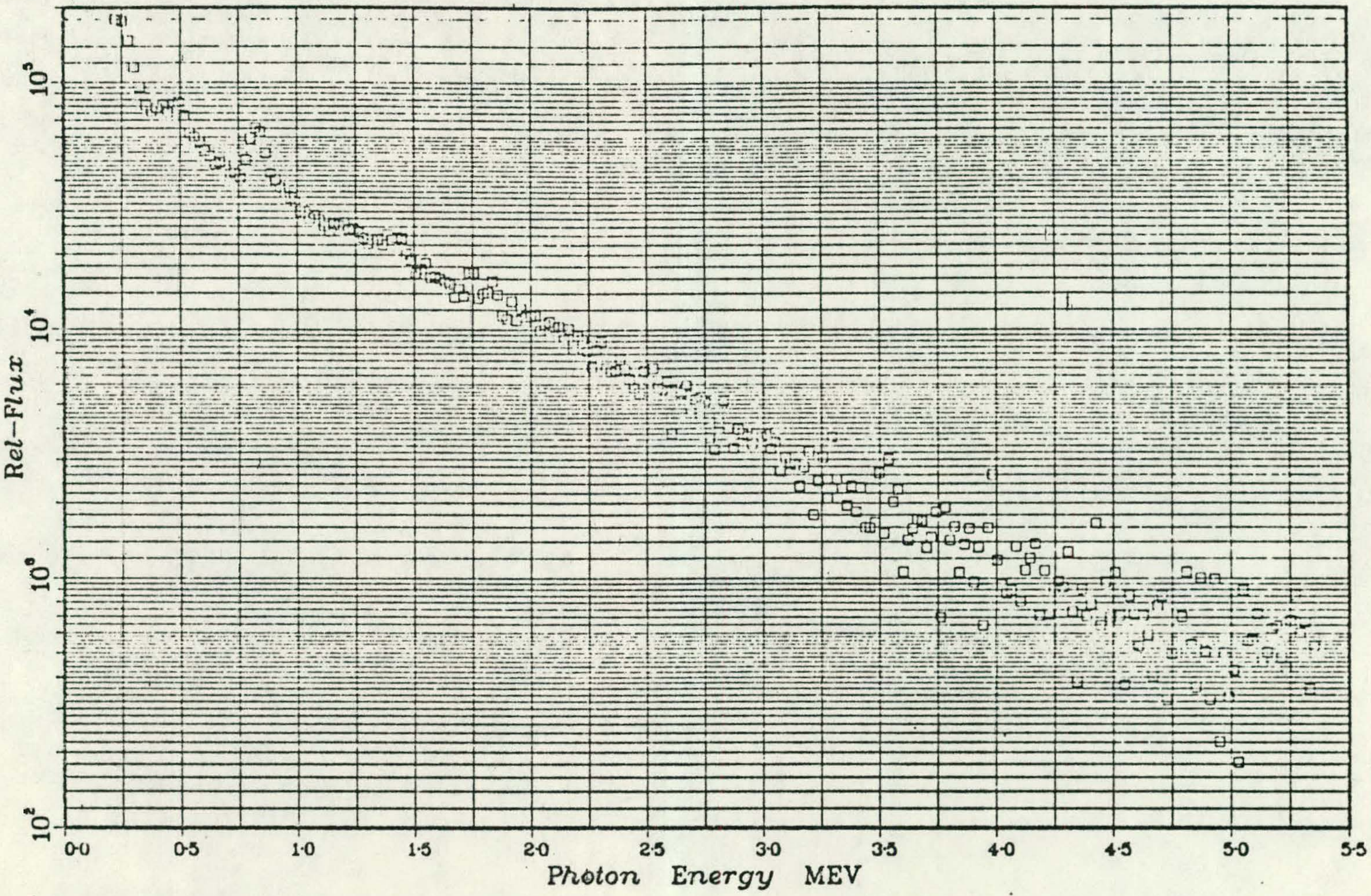

FIGURE 7b. Unfolded Gamma-Ray Continuum Attained at FFTF Upper Axial Reflector in the Lower Power Level Irradiation.