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SUMMARY

A brief description of the optoelectronic feedback system is followed by an account of some interesting aspects of low-noise preamplifiers and detectors revealed by this work. These include the following items:

a. The observation of hole collection at the gate of a FET analogous to ion collection at the grid of a vacuum tube.

b. Mechanical failure modes of light-emitting diodes when cycling their temperature to and from 77°K.

c. A counting-rate effect due to the mean current in the feedback path. This naturally leads to a philosophical discussion of the equivalence of resistor and light-coupled feedback systems. It also suggests the potential advantages of using a pulsed, rather than dc, feedback system.

We also report the use of the optoelectronic feedback system for the observation of a Fano factor of 0.08 or less for a germanium detector.

INTRODUCTION

Work on ultra-high resolution spectrometer systems using semiconductor detectors has been excessively time-consuming and, for the most part, frustrating. To my knowledge this remark has been true (if we include ionization chambers) for the past 25 years, although the details have changed. For some areas - specifically for high-energy γ-rays (i.e. > 500 keV) - statistics of charge production in the detector have become a large and perhaps dominant contributor to the resolution, and the preamplifier noise is a minor factor. However, at lower energies electronic noise is still the major limitation.

The frustrating aspects of work in this area stem in part from our total dependance on chance developments in other areas of electronics, such as low-noise field-effect transistors. This means that our work involves evaluating and selecting components, which is not the most exciting of jobs. It is made more complicated by our use of components at low temperatures, a factor which at once renders manufacturer's specifications meaningless, and furthermore makes the testing cycle long and tedious. True, one can devote one's energy to exploring new methods of filtering signals from noise, and this has been a major diversion for many years. In terms of absolute limits of resolution this work can yield little improvement over existing systems, although secondary factors such as counting-rate effects have been markedly improved as a result of it.

The optoelectronic feedback system, which is the subject of this paper, represents a significant attempt to remove one frustrating element from the game - namely the high-valued biasing resistor in the input circuit. As with all new ideas that make the light of day, we have gained substantially in performance - the idea would have been rejected had that not been so - but new questions, both philosophical and practical, have arisen. Our main purpose here is to discuss some of these new factors, following a brief description of the system and its performance.

THE OPTOELECTRONIC FEEDBACK SYSTEM

The main purpose of this system is to eliminate high-valued resistors such as the feedback resistor R_f in the typical charge-sensitive preamplifier shown in Fig. 1. This removes the associated problems which include:

1. Frequency dependence of the resistive part of the impedance due to distributed capacity and possibly intrinsic effects in the resistive layer. The change in resistive component of a typical 1000 MΩ resistor is shown in Fig. 2. When the input circuit time-constant is long compared with the characteristic time-constant of the amplifier shaping network, the noise produced by a resistor is proportional to $R^{-1/2}$, where R is the value of its resistive component in the frequency range of interest. Generally speaking, the passband of nuclear pulse amplifiers is centered about a frequency

near 100 kHz. The fall-off in the resistive part of the impedance of the feedback resistor R_f is therefore seriously detrimental to the signal/noise ratio.

A further adverse effect, resulting from the change in R with frequency, is that the response of the charge sensitive stage to a step-function input cannot be characterized by a single time-constant. Consequently, pole-zero cancellation methods are not as successful in improving high-rate performance as they might otherwise be.

2. The feedback resistor, generally being rather large physically, adds stray capacity to ground, thereby degrading the signal/noise ratio.

3. High-valued resistors usually contain extraneous noise sources - probably due to their construction.

4. High-valued resistors frequently exhibit peculiar behaviour at low temperatures. This may involve large changes in value, excessive noise, or complete failure. Even if such effects are not observed on the first cooling cycle, they may appear on later ones.

In the optoelectronic system shown in Fig. 3, the feedback resistor is replaced by light feedback obtained by connecting a light-emitting diode to the output of the stage and directing some of the light from it onto a reverse-biased photodiode which connects to the input of the stage. It can be seen that the current in the photodiode is proportional to the output voltage if the light intensity is proportional to the current through the light-emitting diode, (which is true over a small range of currents) and if the photodiode response is linear. We can therefore regard the circuit as being equivalent to a feedback resistor whose value can be varied by adjusting the light coupling. Equivalent resistor values ranging from 10^8 to 10^{12} ohms can be achieved. Unlike practical high-valued resistors, the response times of the light-emitting diodes and photodiodes are very short, and the combination results in an equivalent feedback resistor value which is constant up to 10 MHz or more.

A further refinement is possible since the drain-gate diode of the FET is photosensitive and can be used as the photodiode. This eliminates the additional component in the gate circuit, thereby reducing the stray capacity to a minimum. In practice, this means removing the FET from its case - a procedure which seemed doubtful at first sight, but which has been executed very successfully in about 25 samples. Moreover, the elimination of the gate-lead feedthrough has apparently removed a source of noise,* and more consistent results are obtained from a group of transistors after removal from the case.

* This possibility was mentioned by V. Radeka[1] in 1967.

EXPERIMENTAL RESULTS

We have published[2] some experimental results obtained earlier. Since then better results have been obtained, the best (using a silicon detector) being:

Electronic Resolution: 115 eV (FWHM Si)

Resolution on Mn X-rays (5.90 keV): 180 eV FWHM.

Each measurement was carried out with a silicon detector having a capacity of about 1 pF in the circuit and using a Gaussian shaping network with a peaking time of 16 μsec. The change in resolution of a typical system as a function of time-constant using an equal RC integrator - differentiator shaper is shown in Fig. 4, and is compared with the results obtained in a standard resistor feedback system. We see that the main improvement in performance is at the longer time-constants.

Figure 5 shows a typical spectrum for a Si detector on low energy X-rays produced by X-ray fluorescence in a target containing a number of elements. A 1 mil beryllium window in the vacuum chamber wall admitted the X-rays. This window attenuates the Al X-rays (1.49 keV) by about a factor of two and causes a low energy limit of about 1.25 keV to the X-rays which can be measured. As yet we have done no work with a windowless system, but the intrinsic dead layer in the detector (and its 100Å gold covering) is not expected to determine the low energy limit. Instead, the fundamental electronic noise tail might be expected to cause the limit. In practice we generally observe that spurious noise, either microphonic or electrical, can produce many "low energy" counts and great care must be taken to avoid these if very low energy observations at low counting rates are to be made.

In Fig. 6 the data are presented in a different form to indicate the value of the effective Fano factor of this detector. A straight line should result from plotting $[\text{Resolution}]^2$ vs Energy, and, from its slope, a value for the effective Fano factor can be determined. In this particular case, the effective Fano factor is 0.153. We make no claim that this is the fundamental Fano factor for silicon, as variations in the effective value of F depending on factors such as surface conditions of a detector have been observed. It is interesting to note that this same detector exhibited an effective Fano factor of about 0.14 on ^{207}Bi electrons (975 keV) and ^{241}Am γ-rays (60 keV).

We have also used the optoelectronic feedback system with a small germanium detector. In order to fully realize the potential benefits of the system, the germanium detector must be surrounded by a cooled shield to reduce the leakage current generated by infrared radiation[3] from the walls of the chamber. Spectra which show the performance for ^{57}Co and ^{60}Co (at low counting rates) are shown in Figs. 7 and 8. A detailed analysis of the Fano factor for germanium will be made in a later paper, but the results given in Table 1 are presented here to indicate that the fundamental Fano factor cannot be larger than 0.08 - a value much smaller than that generally accepted. The high value observed for the Mn X-rays may be due to the fact that they interact and produce ionization very near the entry window where a field-free region may exist.

An interesting observation made with both silicon and germanium detectors is that the detector leakage can be smaller than the FET drain-gate leakage - an intolerable condition for the simple feedback system shown in Fig. 3. It has therefore sometimes proven necessary to enhance the detector leakage by using a second infrared light shining onto the detector. The large junction periphery of the detector compared with that of the FET leads one to question the quality of the FET processing compared with that of radiation detectors, and suggests that work to improve FETs would be justified.

ADDITIONAL FACTORS

Anomalous Gate Leakage in FETs

In some early observations of the system we were perplexed to find that the gate current of a number of FETs, when operating in their normal mode, increased as the temperature was reduced. Subsequent investigations revealed results similar to those shown in Fig. 9. These curves, taken with the gate-source voltage equal to zero, show that the gate current decreases with decreasing temperature, as expected, but at high drain voltages the reverse is true. For the particular case shown here we see that the gate current increases by almost an order of magnitude when the temperature is changed from

25°C to -150°C if the drain voltage exceeds 11 volts. The breakdown knee occurs at voltages as low as 5 volts in some batches of 2N4416's. It is therefore necessary to operate with drain voltages below 5 volts to avoid the harmful effects of this breakdown.

The breakdown effect in the room temperature curve shown in Fig. 9 was also observed by E. P. Fowler,[4] and he explained this as being due to the injection of holes from the drain contact into the n type channel. This is consistent with the observation that the gate current in the region above the breakdown knee is proportional to the drain current. However, the positive temperature coefficient of the breakdown voltage illustrated in Fig. 9 suggests another explanation which is demonstrated in Fig. 10. Here the behaviour of an n channel epitaxial FET is shown for low drain voltage (i) and for higher drain voltage (ii). When the FET is operating below pinch-off, the electron flow is through the constricted channel. For voltages higher than pinch-off, we assume that the drain current consists of electrons that are injected from the n type source region into the depletion layer and then drift in the electric field to the drain contact. As the drain voltage is raised, electrons traveling across the depletion layer may acquire sufficient energy to produce small avalanches resulting in holes which then are collected by the most negative electrode - the gate. This is analogous to ion collection at the grid of a vacuum tube. The small dimensions of modern FETs cause the field along the channel to reach values in the region of 50,000 V/cm, and slight non-uniformities may result in small avalanches.

The positive temperature coefficient of the breakdown voltage would naturally follow in this model, as the mobility of the electrons exhibits a negative temperature coefficient. The observed linear relationship between drain and gate currents would also be consistent with this mechanism.

We have also shown the mechanism of drain injection of holes as an alternative in Fig. 10, but we believe that the heavy n^+ doping of the drain contact lessens this possibility.

Mechanical Failure of Light-Emitting Diodes

We have found that a large fraction of the light-emitting diodes used in these systems exhibits total mechanical failure following a series of temperature cycles over the range from 300°K to 77°K. This seems to be due to expansion and contraction of the epoxy lens which is included in the light-diode package. Epoxy is molded directly onto the GaAs/GaP diode face, and contraction and expansion of the epoxy results in lead breakage and fracture of the diode chip. We have now obtained diodes with no epoxy lens and have demonstrated that these suffer no breakage on successive cooling cycles.

Counting-Rate Effects

As seen in the earlier part of this discussion, the improvement in resolution is realized mainly when using long filtering time-constants. Using a Gaussian pulse-shaper, peaking times in the 8 to

16 μsec region are optimum. As the great majority of pulse-height analyzers cannot process such long pulses, we have developed a unit which permits some bias cut from the signal, then stretches it and samples the stretched signal for 1 μsec to produce a 1 μsec wide output pulse. A dc restorer is used at the input of the unit (the time-constant of restoration being chosen to minimize degradation of noise performance), and a pulse pile-up rejection scheme is included in it.

The counting-rate behaviour for Mn X-rays in a typical system is shown in Fig. 11 to illustrate the performance for various peaking times in the Gaussian shaper. Serious degradation of performance occurs at about 2000 cps for the 16 μsec peaking time and at appropriately higher rates for the shorter peaking times, but the low-rate behaviour is best for the 16 μsec peaking time. These results may suggest that fluctuations of baseline in the dc restorer are responsible for the degradation in performance. However, further study reveals that a new, and more interesting, aspect of the high counting-rate behaviour causes about half the degradation in resolution.

In the optoelectronic feedback system shown in Fig. 3, the effect of the negative feedback is to make the average current in the photodiode equal to the average current in the detector. In the absence of radiation this means that the photodiode current is equal to the detector leakage current, and the total noise due to the two currents, which are not correlated, is $\sqrt{2}$ times that due to the detector leakage alone. At high counting rates the average detector current increases, causing an increase in the photodiode average current which introduces additional noise.

Since a counting rate of 10^4 cps of 20 keV X-rays produces an average current of 10^{-11} A, whereas the normal detector leakage is only about 10^{-13} A, this effect is not negligible. If the shaping network has a long time-constant, fluctuations in the feedback photodiode current can clearly become the dominant source of noise. The contribution of this component of the resolution should increase in proportion to (counting rate)$^{1/2}$, and the curve in Fig. 11 for a 16 μsec Gaussian shaper does behave approximately in this way. Calculation of this contribution indicates that it causes almost half the degradation in resolution at 8000 cps; presumably the remainder is due to base-line fluctuations, and possibly non-linear behaviour of the amplifier chain.

Therefore, we are apparently observing a new and interesting phenomenon that causes a degradation of resolution at high counting rates. From a practical point of view we can eliminate this problem by using some method of pulsed light feedback like that of Kandiah and Stirling[5], rather than dc feedback, to maintain the charge sensitive stage near its correct operating point. Logical techniques can then be used to eliminate the false signals which appear at the output of the amplifier when the feedback system is pulsed. Since the photodiode then passes no average current, this noise source is eliminated.

Even dc current in the photodiode, which normally balances the detector leakage, is eliminated; so the resolution at low counting rates is improved.

While this technique solves the problem of removing this source of noise, philosphically it is intriguing to investigate the reason for a rate dependence due to the feedback in the optoelectronic system, since previous work has indicated no similar behaviour in resistor feedback systems. Two approaches are used in noise analysis:

1. Nyquist's theory is used to calculate the resistor noise, and the result is independent of the dc voltage across the resistor. As shown earlier, the light-feedback system can be represented by an equivalent circuit containing a resistive feedback element, and it might be expected that the noise behaviour would be the same as for the equivalent resistive feedback system.

2. On the other hand, simple analysis of the optoelectronic system is based on the current noise in a saturated photodiode, and the mean-square noise is proportional to the average current in the diode. This contrasts with the result obtained by the Nyquist approach which indicates no dependence of noise on mean current.

Our attempts to reconcile the two points of view have not been totally successful, but our present feeling is that the Nyquist approach is not applicable to high-valued resistors. Certainly, if the resistor is made from a semiconductor (and its very high value suggests that practical resistors in this range are), it can be shown[6] that a transition from normal resistor noise (thermal agitation noise) to current noise occurs when electric fields present in the bulk of the material exceed a small value. The physical basis for this is the fact that before recombining, thermally produced carriers travel further because of the electric field than they do because of thermal agitation.

Unfortunately, the undetermined physical nature of high-valued resistors makes any complete analysis impossible, but the behaviour of the light-coupled feedback system strongly suggests that there are fundamental reasons for reconsidering the analysis of noise introduced by high-valued resistors. The existence of rather gross defects in the behaviour of high-valued resistors makes experimental confirmation of these suspicions rather difficult.

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FOOTNOTE AND REFERENCES

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5. K. Kandiah, and A. Stirling, A direct-coupled pulse amplifying and analyzing system for nuclear-particle spectroscopy in Semiconductor Nuclear-Particle Detectors and Circuits, National Academy of Sciences, Publication 1593, p. 495 (1969).

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FIGURE CAPTIONS

1. Block diagram of typical charge-sensitive preamplifier.

2. Behaviour of 1000 MΩ resistor with frequency.

3. Block diagram of optoelectronic feedback system.

4. Change in resolution with time-constant for the two systems using equal RC integrator - differentiator shaping networks.

5. Low energy X-ray spectrum. The source is aluminum potassium sulphate glued to an Al backing plate by silicone varnish. Fluorescence excitation is provided by the Mn X-rays from an ^{55}Fe source.

6. Plot of [Resolution]^2 vs. Energy to determine the Si Fano factor.

7. Spectrum of ^{57}Co using a thin window Ge detector and the opto-electronic system.

8. Spectrum of ^{60}Co.

9. Plot of FET gate current vs. drain voltage at two temperatures.

10. Diagram showing the operation of an FET.

11. System behaviour at different counting rates for Mn X-rays.

TABLE I

Ge detector resolutions for different energies.

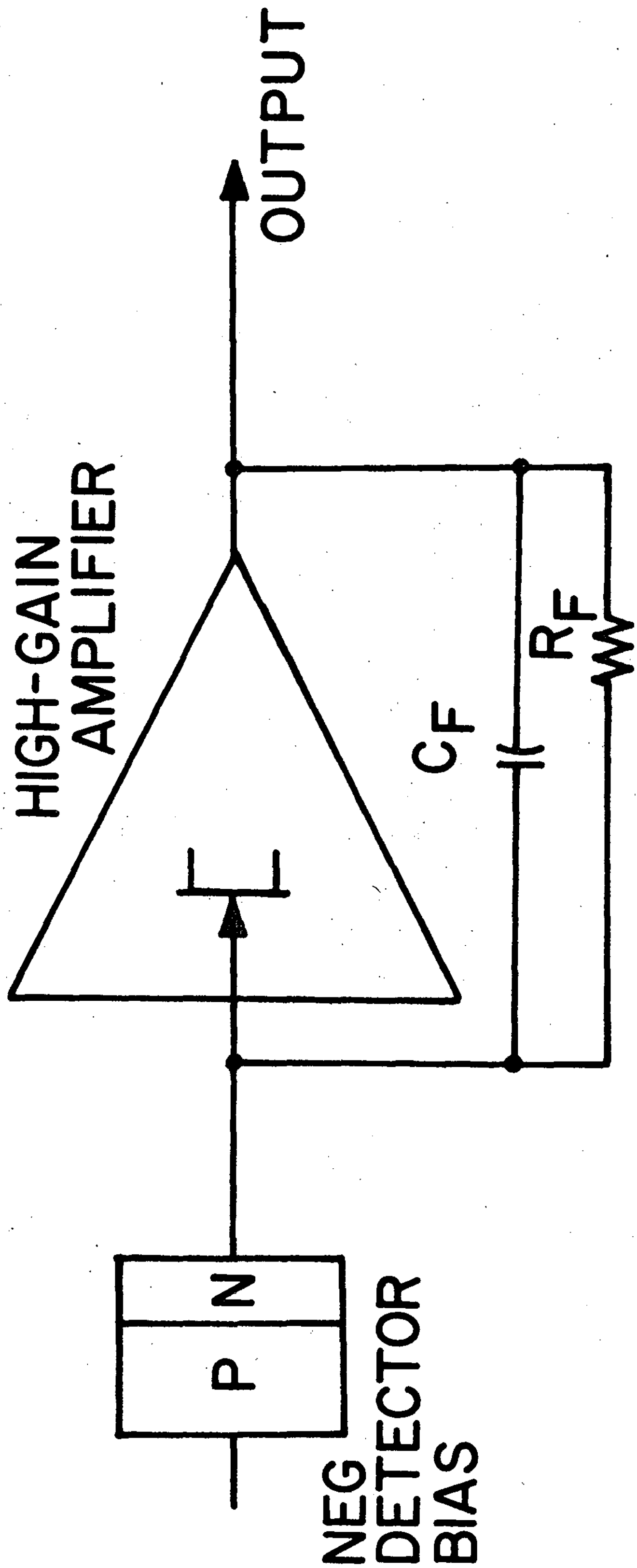


FIG.1:

XBL 692-169

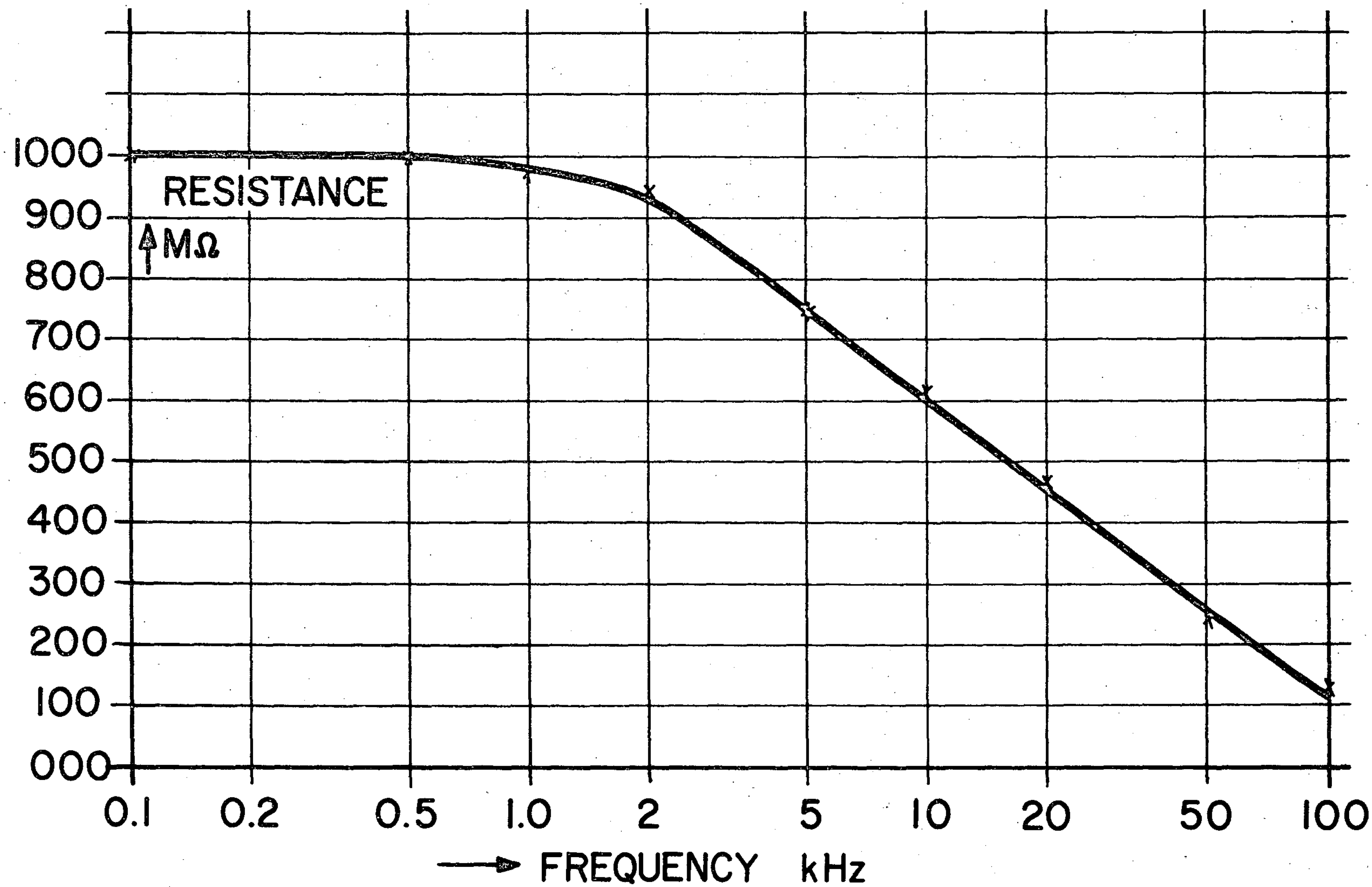


FIG. 2

XBL 692-170

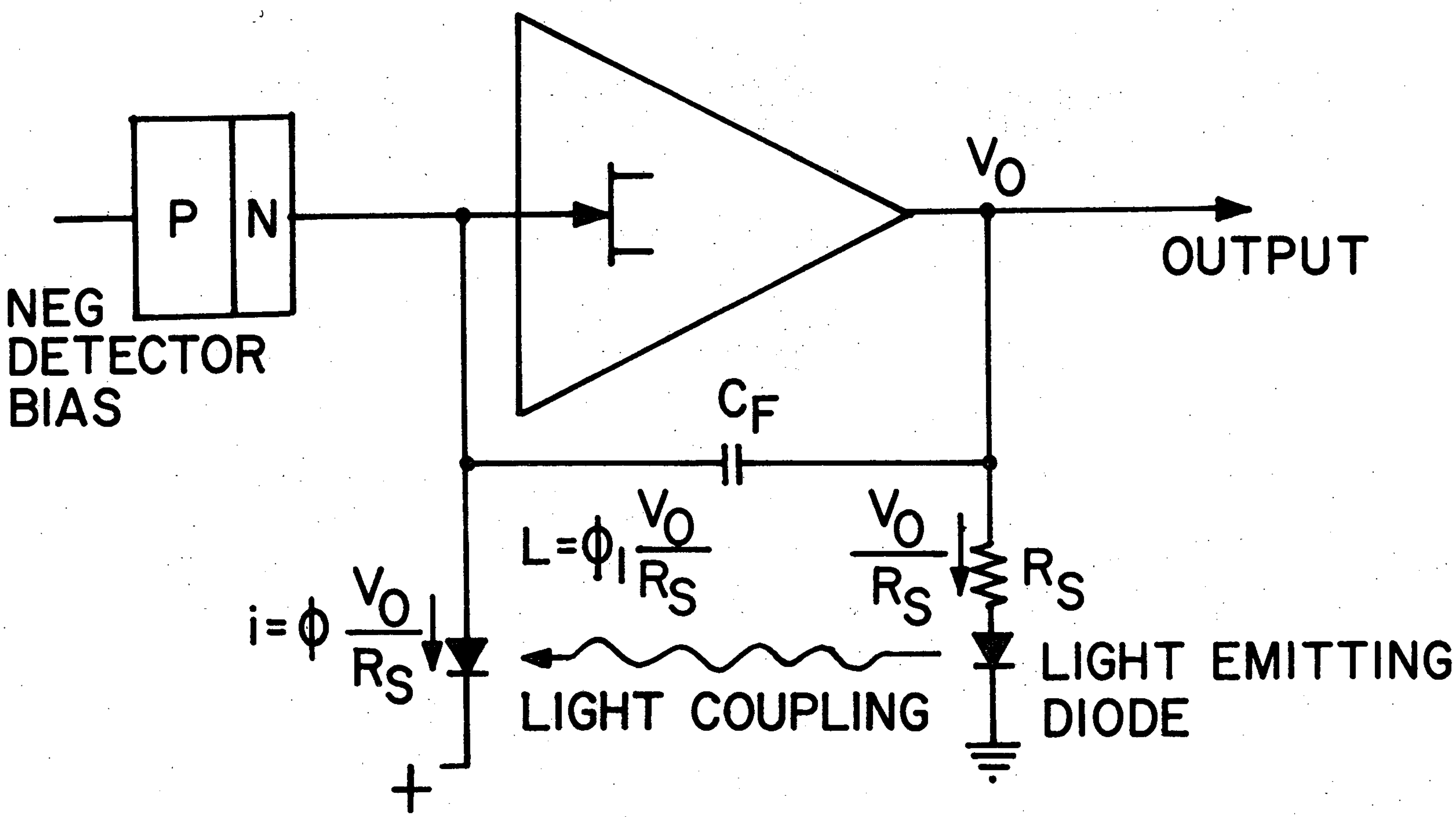


FIG.3:

XBL 692-171

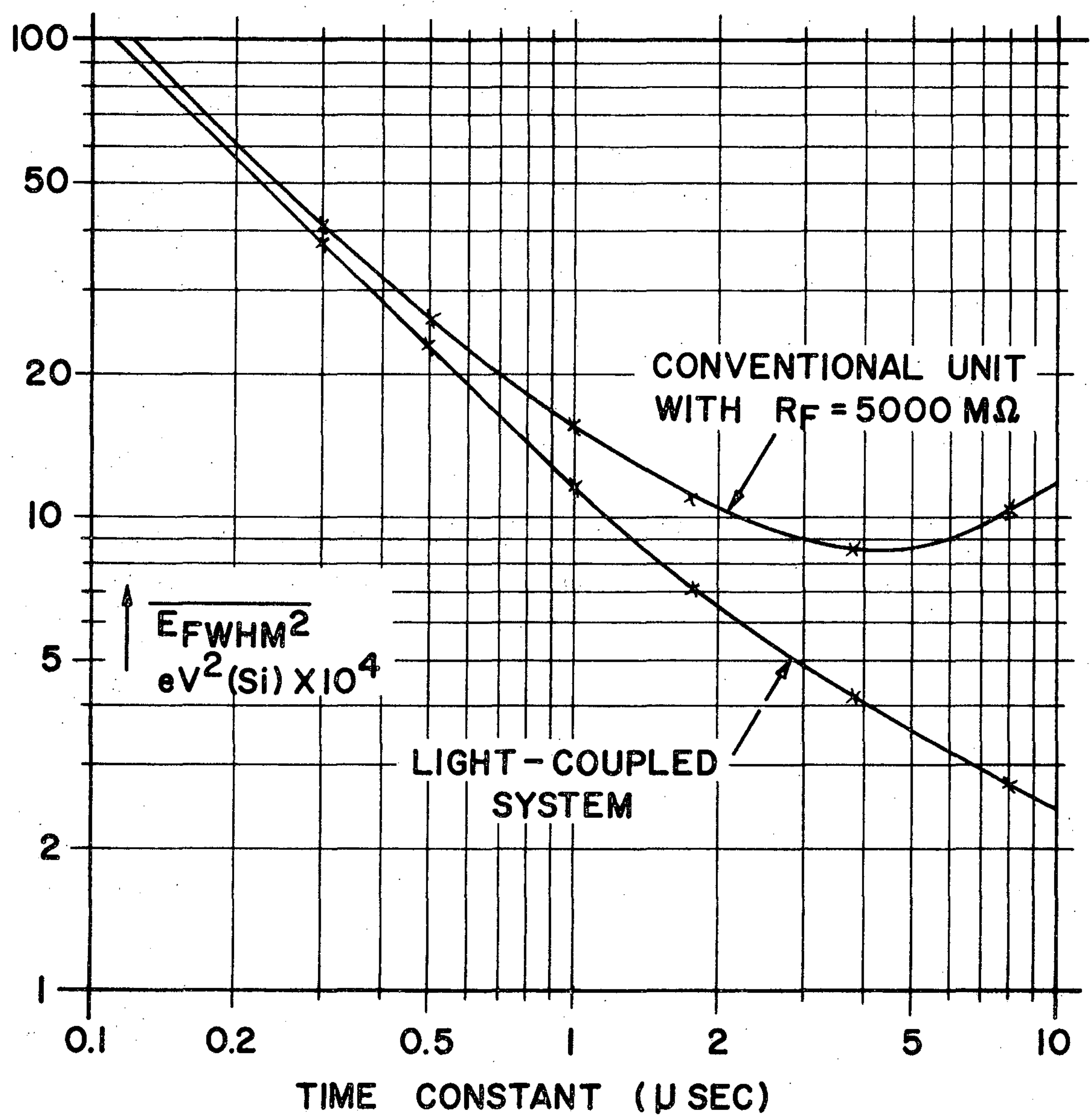
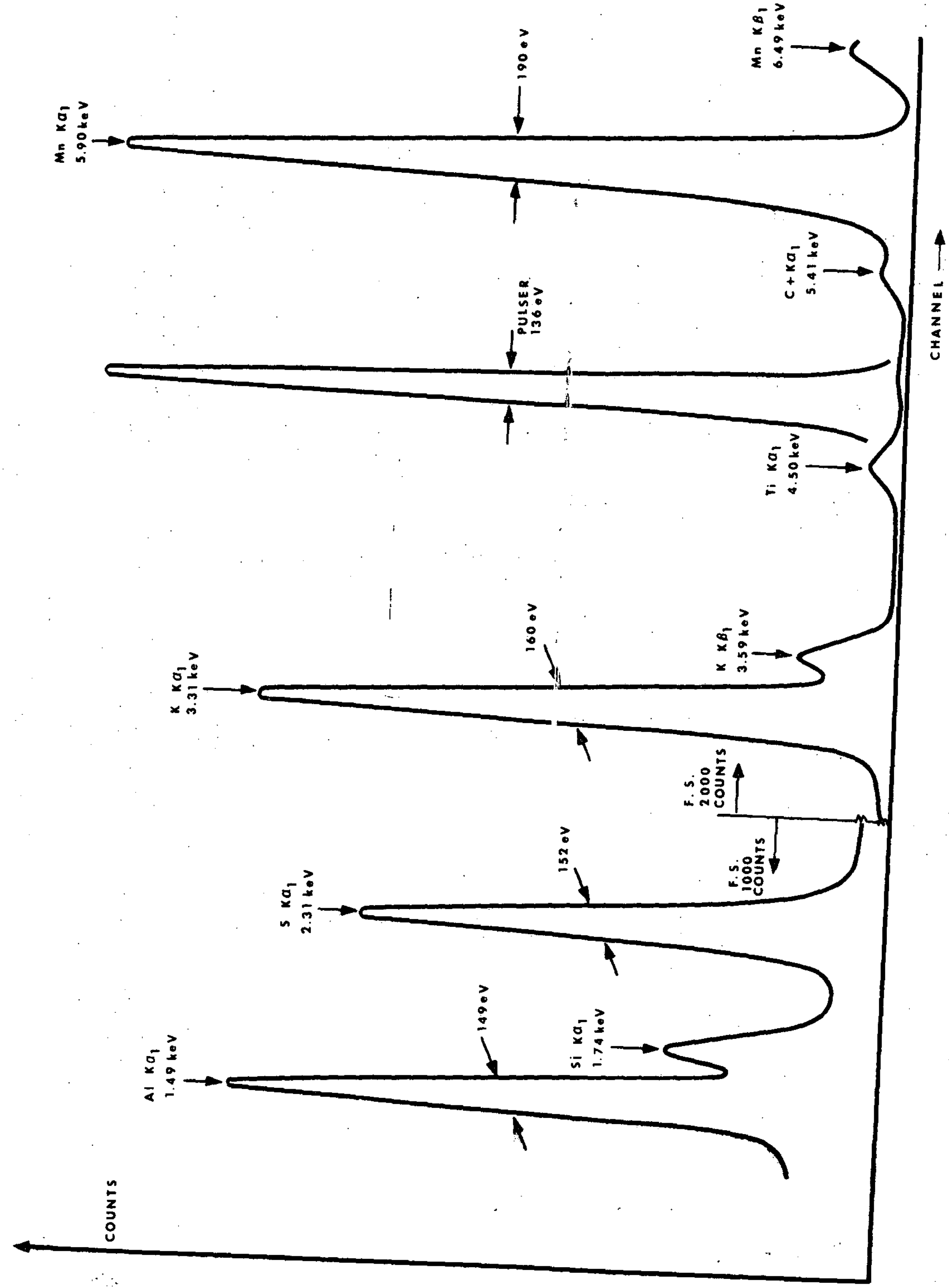


FIG. 4:

XBL 692-173



COUNTS
CHANNEL
Al Kα1
1.49 keV
149 eV
Si Kα1
1.74 keV
S Kα1
2.31 keV
152 eV
F.S.
1000
COUNTS
F.S.
2000
COUNTS
K Kα1
3.31 keV
160 eV
K Kβ1
3.59 keV
Ti Kα1
4.50 keV
PULSER
136 eV
C + Kα1
5.41 keV
Mn Kα1
5.90 keV
190 eV
Mn Kβ1
6.49 keV

Fig. 5

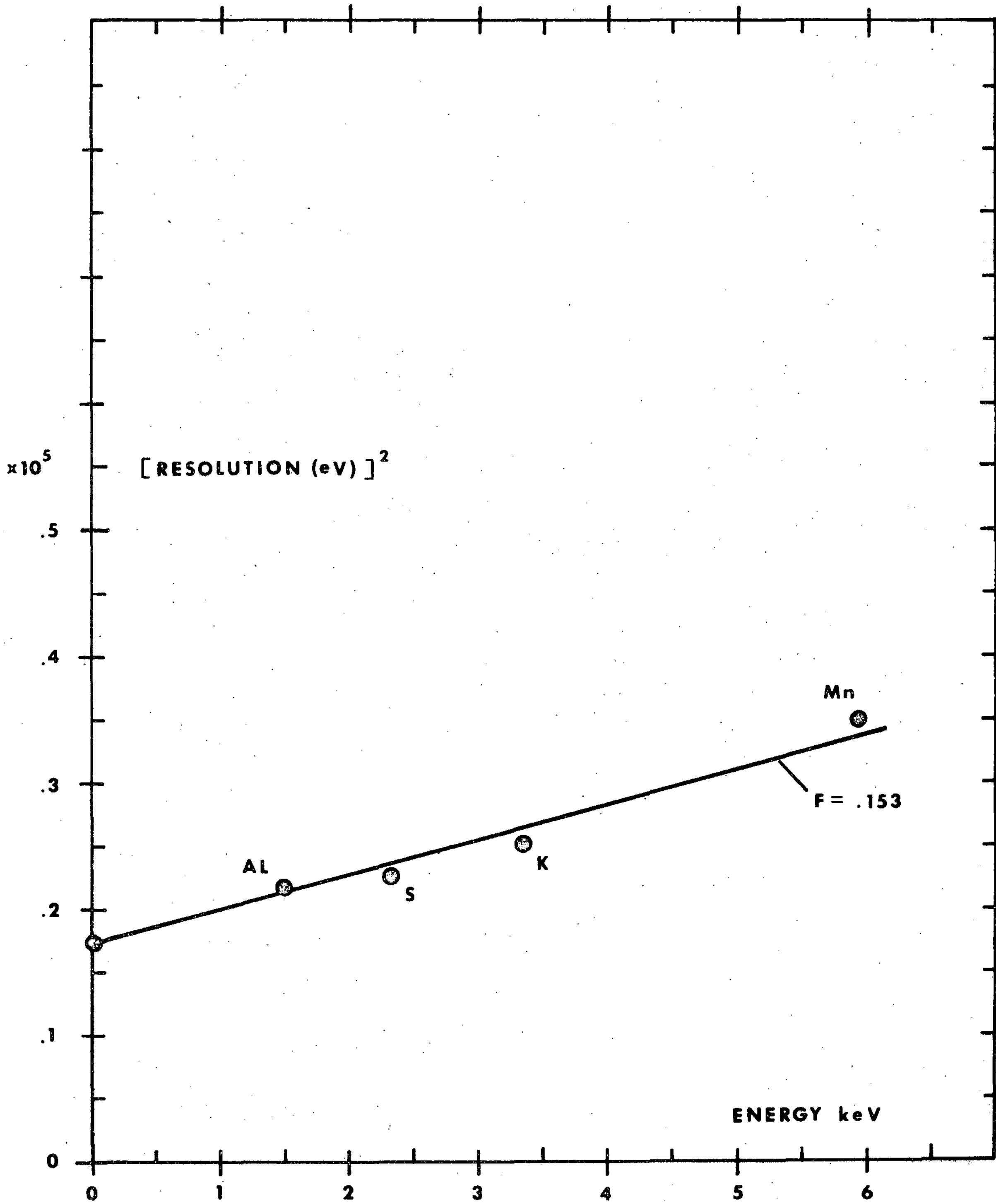


Fig. 6

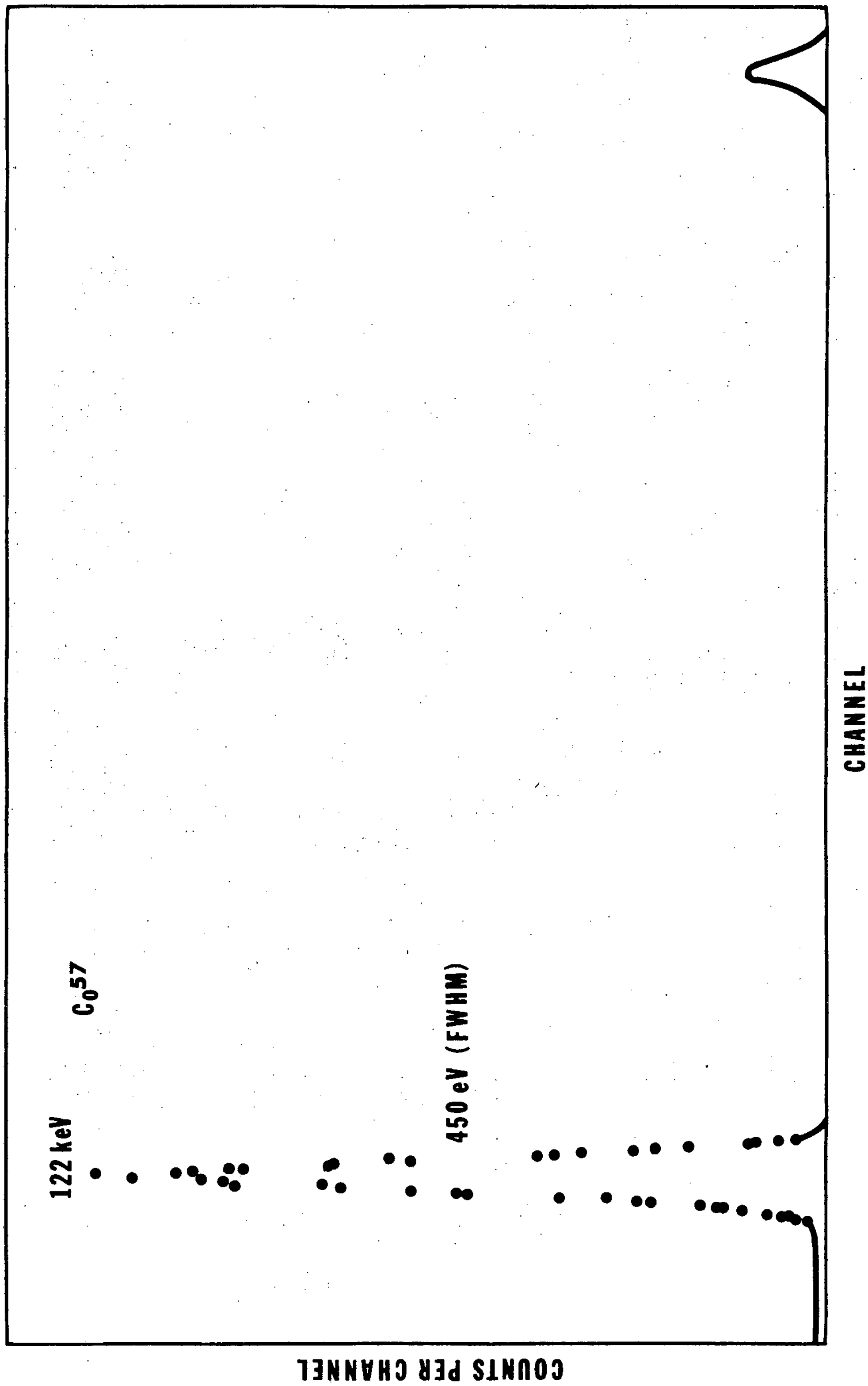


Fig. 7

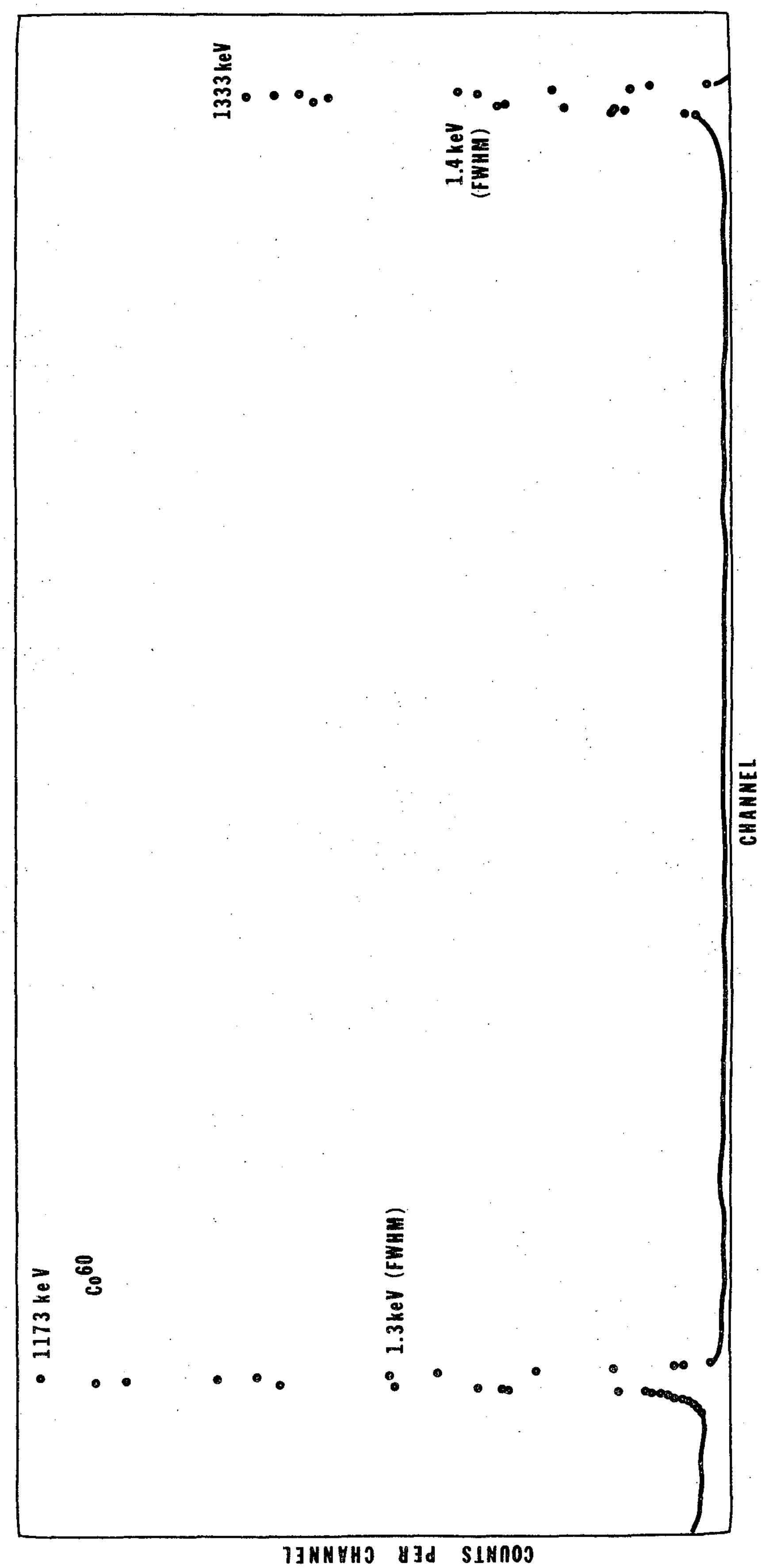
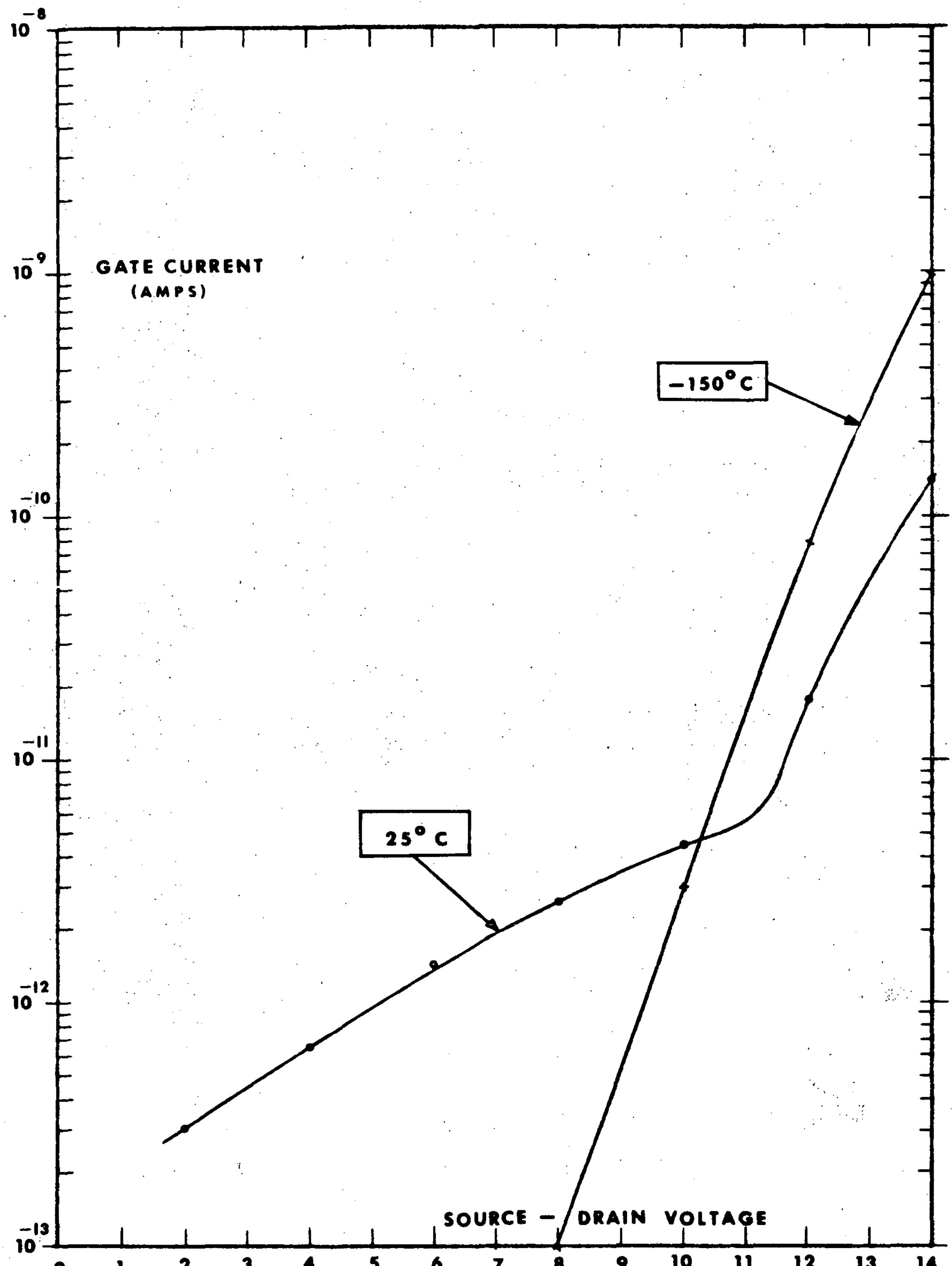
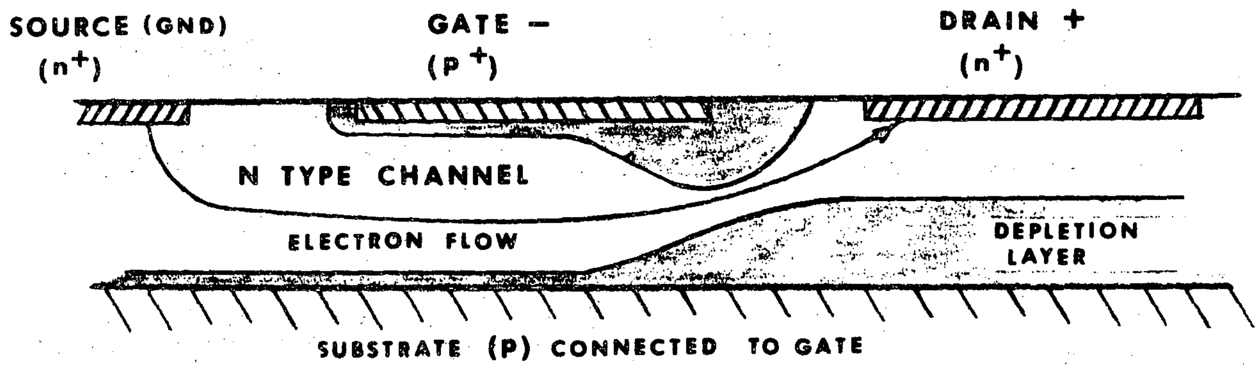

1333 keV
1.4 keV (FWHM)
1173 keV
Co60
1.3 keV (FWHM)
CHANNEL
COUNTS PER CHANNEL

Fig. 8

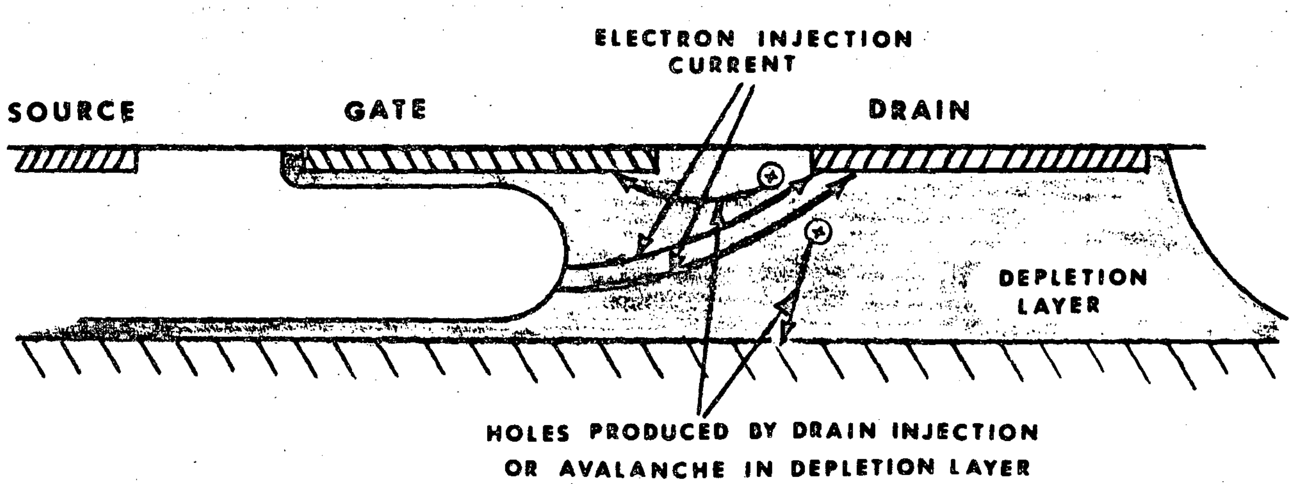


GATE CURRENT (AMPS)
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
−150° C
25° C
SOURCE — DRAIN VOLTAGE
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14

Fig. 9

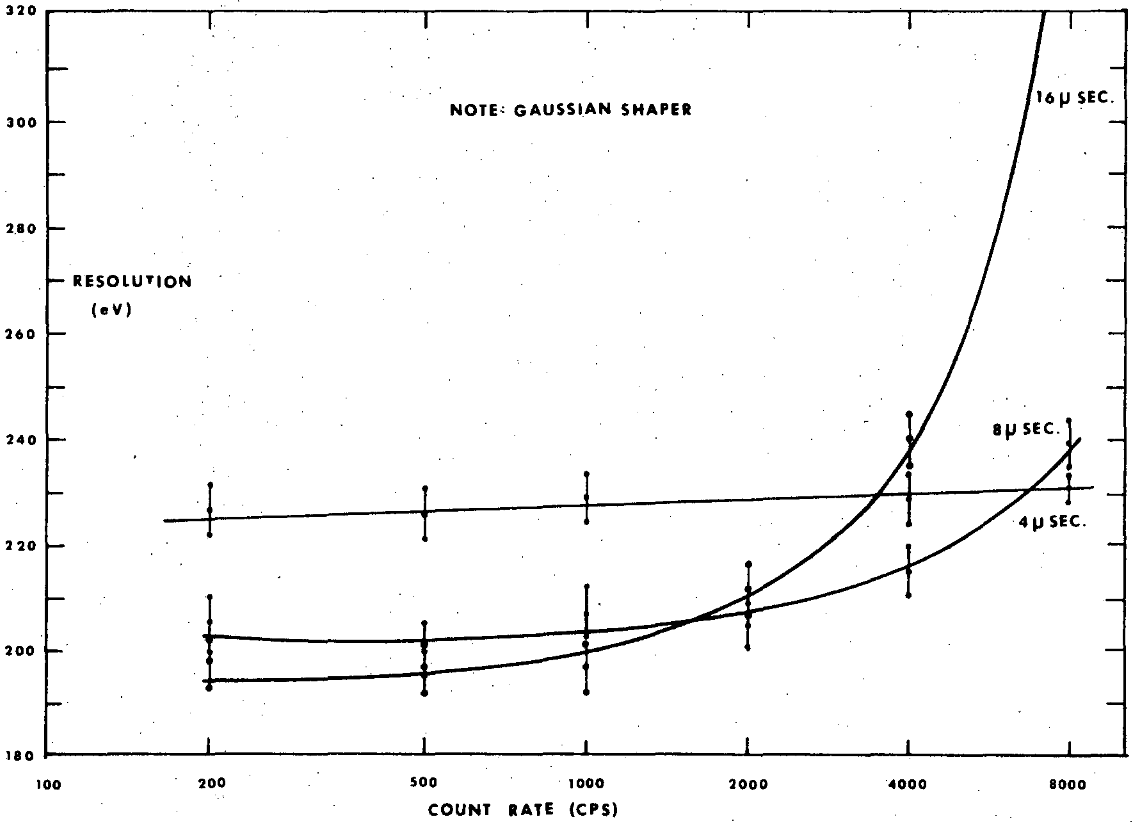


(i) OPERATION BELOW PINCH-OFF REGION



(ii) OPERATION AT HIGH DRAIN VOLTAGES

Fig. 10



XBL 6910-5807

Fig. 11

TABLE 1: Ge DETECTOR – RESOLUTION VS ENERGY

SOURCE	ENERGY	RESOLUTION	PULSER	FANO FACTOR
Co^{60}	1173 keV	1.23 keV	194 eV	.077
Cs^{137}	662 keV	924 eV	150 eV	.0765
Co^{57}	120 keV	450 eV	185 eV	.083
Np (Xray)	13.9 keV	218 eV	177 eV	.070
Mn (Xray)	5.90 keV	183 eV	142 eV	.137

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