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**IEEE Test Procedure for
Amplifiers and Preamplifiers for
Semiconductor Radiation Detectors**

(For Ionizing Radiation)

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FOREWORD

Semiconductor radiation detectors have come into widespread use in recent years for detection of ionizing radiation. Both silicon and germanium detectors have been developed with silicon finding its principal application in the detection and analysis of heavy charged particles. Germanium detectors with their relatively high atomic number (as compared with silicon) and with large sensitive volumes have come into widespread use in the detection and analysis of gamma radiation. The advent of semiconductor detectors has stimulated development of electronic instruments with characteristics that permit exploitation of their capabilities. This has made desirable standard test procedures so that measurements may have the same meaning to all manufacturers and users.

This Test Procedure is not intended to imply that all tests described herein are mandatory, but only that such tests as are carried out should be performed in accordance with the procedures herein.

A companion document is "Test Procedure for Semiconductor Radiation Detectors," IEEE Standards Publication No. 300.

The Institute wishes to acknowledge its indebtedness to those who have so freely given of their time and knowledge, and have conducted experimental work on which many of the IEEE publications are based.

This publication was prepared by the Radiation Detectors Committee of the IEEE Nuclear Science Group. The membership of the Committee was:

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CONTENTS

1. General	3
1.1. Symbols	3
1.2. Types of Pulse Distortion	4
1.3. Simulating the Charge Pulse of a Detector	4
1.4. Specifying Amplifier Noise	4
1.5. Specifying Amplifier Nonlinearity	5
2. Noise, or Linewidth, Measurements	5
2.1. Noise Measurement by Pulse-Height Distribution	5
2.2. Noise Measurement by Oscilloscope and Root-Mean-Square Voltmeter	6
3. Preamplifier Noise Performance	6
3.1. CR - RC Shaping	6
3.2. Measurement of Equivalent Noise Resistance	7
3.3. Noise as a Function of External Capacitive Loading	9
4. Main Amplifier Noise	9
4.1. Equivalent Noise Referred to Input	9
4.2. Influence of Main Amplifier Pulse Shaping on Preamplifier Noise	10
5. Pulse-Height Linearity	10
5.1. Integral Nonlinearity Measurement by the Bridge Method	10
5.2. Differential Nonlinearity	11
5.3. Biased Amplifiers	12
6. Count-Rate Effects	12
6.1. Pulse-Height Distribution Peak Shift	12
6.2. Spectral Line-Shape Change	12
7. Overload Effects	13
7.1. General	13
7.2. Amplifier Gain Recovery Time	13
8. Pulse-Height Dependence on Rise Time	14
8.1. General	14
8.2. Capacitive Loading Effects on the Preamplifier Output Pulse	14
8.3. Capacitive Loading Effects on System Output-Pulse Height	14
8.4. Influence of Charge-Pulse Duration on Pulse Height	15
9. Pulse-Height Stability	15
9.1. Line Voltage Variations	15
9.2. Temperature Effects	16
9.3. Gain Stability	16
10. Crossover Walk	16
10.1. Crossover Walk versus Output Amplitude	16
10.2. Crossover Walk versus Gain Control Setting	16
11. References	16
12. Glossary	17

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1 GENERAL

1.1 Symbols

a, b	Constants characterizing noise.	I	Electric current.
B	Bandwidth.	I_d	Detector leakage current.
C	Electrical capacitance.	I_0	Diode equivalent Gaussian noise current in a specified frequency band.
C_c	Calibrated capacitor used to couple pulse generator to circuit under test.	k	Boltzmann's constant.
C_{eff}	Effective input capacitance of a preamplifier.	K	Constant relating FWHM in units of energy to FWHM in units of charge.
C_f	Feedback capacitance in the charge-sensitive loop of a preamplifier.	L_D	Differential nonlinearity of an amplifier.
C_t	Total capacitance at preamplifier input.	L_i	Integral nonlinearity of a biased amplifier.
Δ	FWHM of a monoenergetic spectral peak.	L_I	Integral nonlinearity of an amplifier.
Δ_A^A	FWHM, expressed in units of energy, due to amplifier noise.	N	Channel number corresponding to the maximum of a monoenergetic spectral peak.
Δ_A^A	FWHM, expressed in channels, due to amplifier noise.	N_{avg}	Average number of counts in all channels of a multichannel pulse-height analyzer spectrum.
Δ_A^Q	FWHM, expressed in units of charge, due to amplifier noise.	N_X	Number of counts in channel X of a multichannel pulse-height analyzer spectrum.
Δ_B^D	FWHM, expressed in units of energy, due to detector noise.	Q	Electric charge.
Δ_B^D	FWHM, expressed in channels, due to detector noise.	R	Electrical resistance.
Δ_B^Q	FWHM, expressed in units of charge, due to detector noise.	R_c	Resistor used in parallel with C_c to effect pole-zero cancellation.
Δ_N^D	FWHM, expressed in channels, due to detector noise.	R_L	Detector load resistor.
Δ_N^Q	FWHM, expressed in units of charge, due to detector noise.	R_p	Parallel equivalent noise resistance.
Δ_N^O	FWHM, expressed in channels, due to all factors other than electric noise.	R_s	Series equivalent noise resistance.
Δ_N^S	FWHM for monoenergetic incident radiation, expressed in channels, including all spectral broadening effects.	R_{SN}	Resistance of a resistive summing network.
Δ_B^T	FWHM, expressed in units of energy, due to the combined effect of detector and amplifier noise.	T	Absolute temperature.
Δ_N^T	FWHM, expressed in channels, due to the combined effect of detector and amplifier noise.	t_c	Charge collection time in a detector.
Δ_Q^T	FWHM, expressed in units of charge, due to the combined effect of detector and amplifier noise.	t_o	Observed detector rise time due to the combined effects of the charge collection time and detector electrical rise time.
E	Energy of a particle or photon.	t_p	Detector electrical rise time.
ϵ	Average energy required to form one hole-electron pair.	t_r	Rise time (10–90 percent).
e	Electron charge.	τ	Time constant.
e_{ni}	Equivalent root-mean-square noise voltage referred to the preamplifier input.	τ_c	Time constant of a CR network used to simulate the rise of a pulse from a radiation detector.
e_{ns}	Root-mean-square noise voltage.	τ_d	Decay time constant.
e_{ni}	Root-mean-square noise in units of charge at the amplifier input.	V	Electric voltage.
φ	Noise spectral power density.	V_o	Amplitude of amplifier output voltage.
i	Detector noise current.	V_d	Detector bias voltage.
		V_s	Amplitude of the voltage signal output of an amplifier during measurement of amplifier linearity.
		ΔV_s	A voltage difference signal related to the nonlinearity of an amplifier.
		V_s	Amplitude of the voltage step impressed on C_c by the pulse generator.
		V_t	Threshold bias voltage of a biased amplifier.
		ω	Angular frequency.
		Z_o	Characteristic impedance.

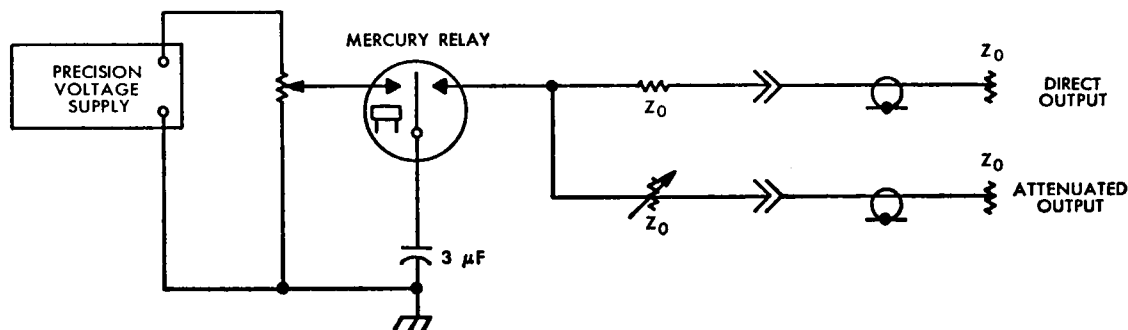


Figure 1.3.1. Precision pulse generator.

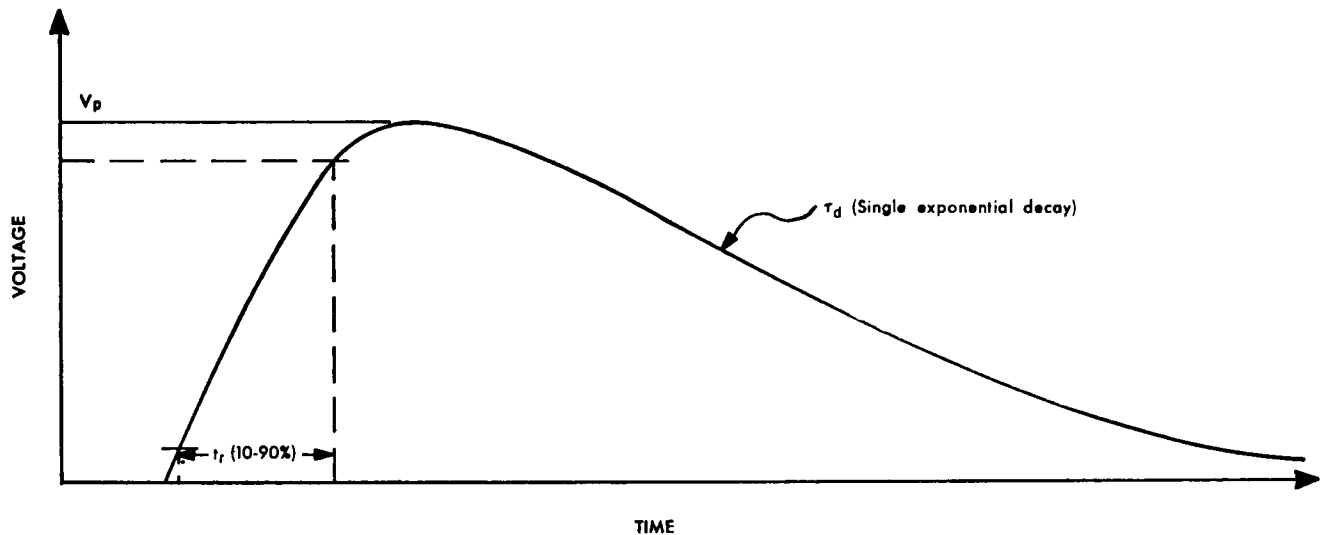


Figure 1.3.2. Precision pulse generator waveform.

1.2 Types of Pulse Distortion. The electronics for semiconductor radiation detectors are usually selected to complement some or all of the useful characteristics of these detectors: good resolution, fast pulse rise time, excellent energy linearity, and low inherent noise. The performance of any component of an electronics system can be described in terms of deviations from ideal behavior. Since the detector user seeks pulse-height and timing information, it is reasonable to specify amplifier performance in terms of pulse-height spectral distortion and timing distortion. It is essential that the hum and ripple not influence the measurements substantially.

1.3 Simulating the Charge Pulse of a Detector. The output of a semiconductor detector is a quantity of charge. This charge amounts to a current pulse lasting $\sim 10^{-9}$ to $\sim 10^{-6}$ second, depending upon bulk resistivity, bias voltage, type and orientation of ionizing event, etc. This charge pulse can be simulated by applying a voltage step to a small capacitor connected in series with the preamplifier input. A suitable voltage step can be produced by a mercury-wetted-contact relay type of pulser [F3]. The circuit diagram of a typical pulser and its output-pulse waveform are shown in Figures 1.3.1 and 1.3.2. If the series capacitor C_s of Figure 2.1.1, is very small compared

with the dynamic input capacitance of the preamplifier under test, the charge Q delivered to the amplifier is

$$Q = C_s V_p, \quad (1.3.1)$$

where C_s is the value of the series capacitor and V_p is the amplitude of the voltage step from the precision pulser.

A resistor R_s in parallel with C_s is required for the overload and counting rate tests of Sections 6 and 7 [B4], [N2].

Where incorporating R_s would upset the bias condition at the preamplifier input, a large capacitor may be used in series with R_s .

1.4 Specifying Amplifier Noise. The noise performance of an amplifier may be given unambiguously in units of charge [B1], [B2], [F2]. The amplifier noise may be given in root-mean-square number of electronic charges e_n , since the electronic charge is of a convenient size (1.602×10^{-19} coulomb). The user may interpret this specification to his particular application in units of energy (electronvolts) by the relation

$$\begin{aligned} \Delta_E^4 &= 2(2 \ln 2)^{1/2} e(e_{a,i}) \\ &= 2.355 e(e_{a,i}) \end{aligned} \quad (1.4.1)$$

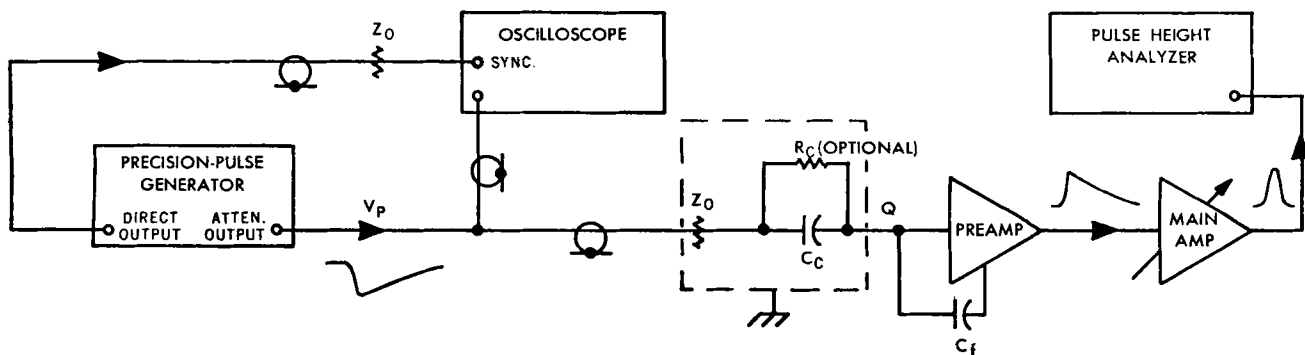


Figure 2.1.1. Measurement of pulse-height distribution linewidth.

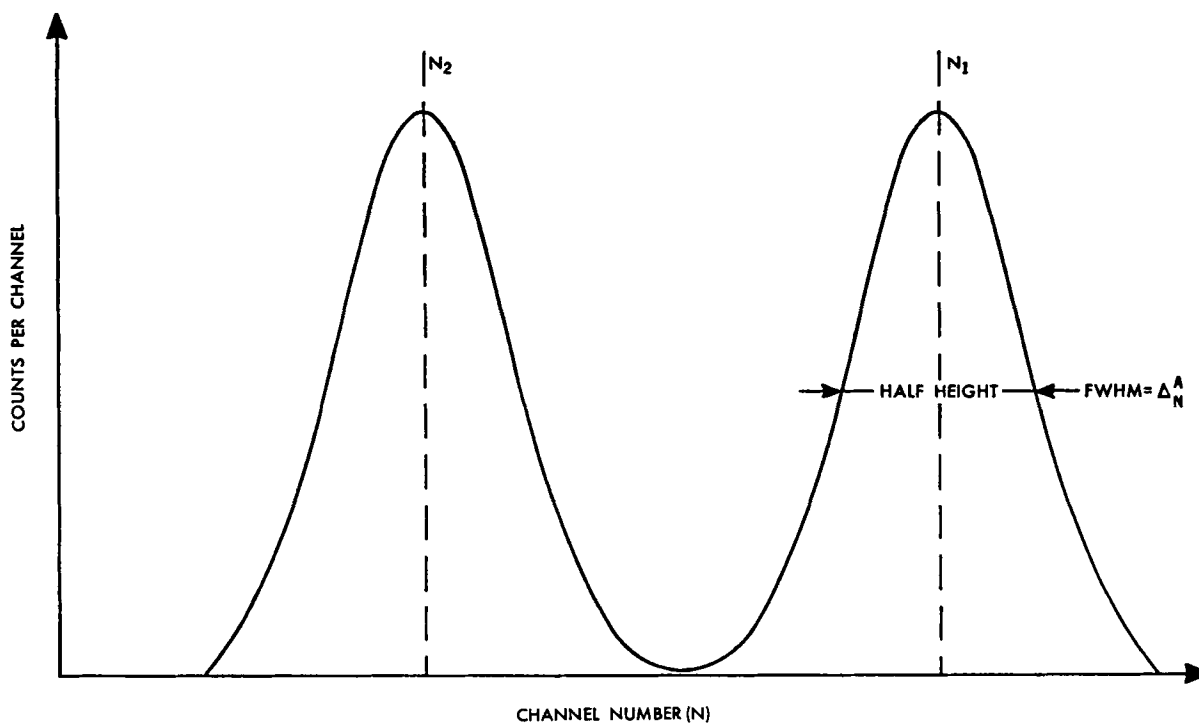


Figure 2.1.2. Typical noise measurement pulse-height distribution.

where ϵ is the average energy expended per electron-hole pair generated in the semiconductor material. (The value of ϵ is presently assumed to be 3.6 electronvolts per pair for silicon at 300 kelvins and 2.9 electronvolts per pair for germanium at 77 kelvins.) If amplifier noise is specified in units of energy, the semiconductor material to which it refers must also be specified. Care must be taken that, for all measurements of resolution, the output-pulse amplitude is within the linear region of the amplifier. Except in the case where an amplifier biases off any portion of the noise, the measurement of noise with a root-mean-square voltmeter is approximately equivalent to noise measurement with a multichannel analyzer.

1.5 Specifying Amplifier Nonlinearity. The pulse-height distortion of a nuclear pulse amplifier caused by amplitude nonlinearity is given in percentage of integral nonlinearity L_I or of differential nonlinearity L_D . Integral nonlinearity is the departure from linear response expressed as a per-

centage of the maximum rated output pulse. Differential nonlinearity is the percentage deviation in incremental amplification of the amplifier referred to some standard point (see paragraphs 5.1 and 5.2).

2 NOISE, OR LINEWIDTH, MEASUREMENTS

2.1 Noise Measurement by Pulse-Height Distribution. The preamplifier and amplifier are connected into a test setup as illustrated in Figure 2.1.1. A pulse-height distribution is accumulated on the multichannel pulse-height analyzer (of at least 100 channels) for at least two settings V_P of the precision pulse generator so that the distribution contains two or more well-separated peaks such as shown in Figure 2.1.2. The system gain and input charge must be adjusted to produce a pulse-height distribution with the full width at half maximum (FWHM) of each peak Δ_N^A exceeding five channels.

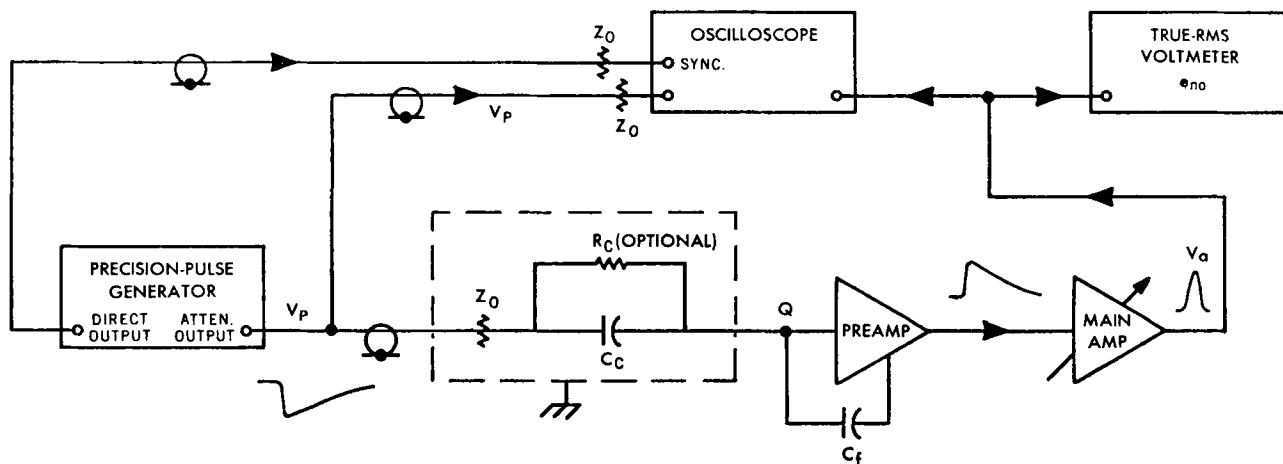


Figure 2.2.1. Noise measurement with oscilloscope and voltmeter.

Care must be taken that the peaks are accumulated in the linear operating region of the system. The system electric noise linewidth Δ_Q^A in units of charge is defined as

$$\Delta_Q^A = \frac{V_{p1} - V_{p2}}{N_1 - N_2} C_c (\Delta_N^A), \quad (2.1.1)$$

where V_{p1} and V_{p2} are the voltage pulse outputs of the precision pulse generator, N_1 and N_2 are the channel numbers corresponding to the maxima of the two peaks, C_c is the value of the calibration capacitor, and Δ_N^A is the FWHM of the pulse-height distribution in channels (see Figure 2.1.2).

The pulse generator should provide signals of the form shown in Figure 1.3.2, where the rise time t_r should be no more than 20 percent of the shortest differentiating time constant in the main amplifier, and the decay time constant τ_d should be such that the pulse height V_p does not droop more than 2 percent in the time required for the output pulse of the main amplifier to reach its peak. A suggested specification is that t_r be < 20 nanoseconds and τ_d be > 100 microseconds. The precision calibration capacitor C_c in series with the precision pulse generator should preferably be of the three-terminal type; that is, the capacitance is measured between two insulated terminals, and the third terminal is ground. A highly accurate measurement of the capacitance between the two insulated terminals may be obtained with a capacitance bridge, and this capacitance is invariant with external circuit connections. Any built-in calibrating capacitor in the preamplifier may be compared with this precision, three-terminal type capacitor. In addition, the dynamic input capacitance of the preamplifier should be not less than 100 times C_c . Under these conditions the charge injected per pulse from the generator is $V_p C_c$ to within approximately 1 percent. A suggested value of C_c is 1 picofarad.

2.2 Noise Measurement by Oscilloscope and Root-Mean-Square Voltmeter. The noise in a complete amplifier system can be measured by use of an oscilloscope and a root-mean-square voltmeter [F1], [F2], [F4]. A test setup is shown in Figure 2.2.1. A charge pulse is applied to the input of

the preamplifier system and the peak amplitude of the output pulse V_a is measured. The root-mean-square noise voltage e_{no} is indicated on a voltmeter having a flat frequency response extending to at least 10 times the band-center frequency of the amplifier pulse-shaping networks and having true root-mean-square response. If a voltmeter that responds to the average value of the input waveform must be used, the scale reading should be multiplied by 1.11 to convert the sine-wave calibration to random noise calibration. A suggested minimum 3-decibel bandwidth for the true root-mean-square voltmeter is 10 megahertz. In addition, the amplifier incremental gain must be constant down to below the noise level; that is, a biased amplifier section would render this measuring technique useless. The presence of large-amplitude pulses will cause erroneous voltmeter readings when the crest factor of the voltmeter is exceeded or at high pulser repetition rates. Therefore, the charge pulser must be turned off while noise voltage readings are taken. The system electric noise linewidth Δ_Q^A in units of charge is given by

$$\Delta_Q^A = (2.355) V_p C_c \frac{e_{no}}{V_a}. \quad (2.1.2)$$

3 PREAMPLIFIER NOISE PERFORMANCE

3.1 CR-RC Shaping. The noise performance of a preamplifier can be measured by the techniques outlined in Section 2 if the preamplifier output is operated on by a completely specified transfer function such as one low-pass RC filter (integrator) and one high-pass CR filter (differentiator) of equal and stated time constants. The performance of this preamplifier, when used with any other pulse-shaping technique, can be calculated from data obtained with simple CR-RC pulse shaping [N1].

When measuring preamplifier noise, it is necessary to verify that noise from the main amplifier does not substantially contribute to the results. For any given set of amplifier settings, the main amplifier contribution can be determined by measuring e_{no} (Figure 2.2.1) with and without the preamplifier connected to the main amplifier. In the latter case the main amplifier input is shunted to