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A WIDE-RANGE COUNTING-CAMPBELLING
NEUTRON-FLUX DETECTION SYSTEM

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A WIDE-RANGE COUNTING-CAMPBELLING NEUTRON-FLUX DETECTION SYSTEM

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I. SUMMARY

Conventionally the wide range of neutron flux that must be monitored in a nuclear reactor has required systems that use two or more types of detectors placed at various locations relative to the reactor core. When such systems are used, suitable discrimination against unwanted gamma, alpha, and noise signals can be difficult to achieve over the entire range of neutron flux. A neutron-detection system that uses a single fixed-position neutron detector to continuously monitor up to ten decades of reactor power has been assembled and tested. Superior gamma discrimination, compared to conventional systems, was realized over the entire neutron-flux range.

A conventional counting technique was used to cover the source and low intermediate ranges, and a statistical chamber current fluctuation technique, sometimes referred to as a "Campbelling System" or "Mean-square Voltage System," was used to monitor the intermediate and power ranges. Sufficient linear overlap of the two output signals was experimentally verified, thus demonstrating the continuous monitoring feature. A mean chamber current measurement was included as part of the system and could have been used for the linear high-power trip signals. With more sophisticated equipment, period trip signals could also have been generated over the entire neutron-flux range.

A standard fission counter operating at 300 volts provided the signal to a bandpass preamplifier. The preamplifier output was connected directly to a linear pulse amplifier-discriminator with a count-rate display, and to true rms and average-magnitude-type voltmeters. The mean-current signal was measured with a picoammeter.

The system response to neutron flux was measured. The true mean-square voltage-output signal is compared to the average-magnitude-squared signal, and the differences discussed. The change in system response when different cables were used between the detector and preamplifier was also measured and compared to that theoretically predicted.

A system of this kind shows particular promise when applied to fast-reactor systems that have large gamma backgrounds, such as EBR-II. This type system also appears to be attractive from a reliability and economic standpoint if applied to other facilities such as the Argonne Advanced Research Reactor (AARR).

In addition, some of the basic pulse parameters of a standard WL-6376 fission counter were measured. The average number of alpha pulses produced by the fissionable detector coating was determined along with the mean and mean-square charge produced per alpha pulse. The neutron-pulse sensitivity of the detector was measured as well as the mean and mean-square pulse charge for neutrons. The average electron-collection time and current pulse shape from the detector for a neutron-produced event were established. The pulse shape at the input and output of the preamplifier was determined and compared to that calculated. In general, all the experimental results are in excellent agreement with the theoretical predictions.

Recommendations for future work are presented, and a typical specification for a prototype ten-decade instrument system is included.

II. INTRODUCTION

Neutron flux is usually measured with a mean-current instrument at intermediate and high neutron-flux levels and with pulse-counting systems at low neutron-flux levels. Two or more different detectors are needed to cover the complete range of neutron flux, which is 9 to 10 decades for high-power reactors. BF_3 proportional or fission counters are used as the detectors at low neutron-flux levels. Individual pulses are produced for each nuclear event, and unwanted pulses caused by alpha- and gamma-ray interactions with the detector, as well as circuit noise, are eliminated by using amplitude-discrimination circuits. Neutron pulses above the discriminator level are counted and displayed on a count-rate instrument. When the average rate of pulse occurrence increases so that the interval between successive pulses approaches the resolving time of the system, the pulses begin to superimpose, and individual events can no longer be identified. When this occurs, other techniques must be used to measure the neutron flux.

The dc component from a detector, usually a boron-coated ion chamber, is used as the signal in the conventional reactor-control system for the intermediate and high neutron-flux ranges. The dc signal represents a combination of all the contributing signals including the unwanted gamma and leakage currents. The unwanted components of the output signal may be comparable to, or even greater than, the output due to the neutrons over a part of the range covered. At high neutron-flux levels, the

ratio of neutron to gamma-plus-noise signal is high, and the unwanted current component is small compared to the desired neutron output. Because of this, uncompensated ion chambers are suitable as detectors at these levels. For the intermediate range, where the gamma-plus-noise signal does contribute significantly to the total output signal, compensated ion chambers must be used. Compensated ion chambers are designed to effectively cancel out the part of the signal caused by the gamma flux. Some of these chambers present operational problems associated with the variable gamma and noise signals generated in power plants. These effects cannot always be detected or predicted.

The intervals between successive pulses at a constant flux level are distributed according to Poisson statistics. Because of this, the detector output signal is composed of a dc. or mean current signal, upon which is superimposed a fluctuating signal due to the randomness of the pulses. The mean-square value of this fluctuating signal is proportional to the product of pulse rate and mean-square pulse charge. If this signal is used to measure neutron flux, an inherent improvement in the discrimination of the alpha and gamma components is achieved. A patent* was issued to Lichtenstein in 1959 for a system based upon this "Mean-square Voltage" principle.

The system used in these tests was composed of a counting channel to cover the source of low intermediate-period range, and a "Mean-square Voltage" (MSV) channel to overlap the intermediate range and continue on into the power range. The system provides reliable gamma discrimination over the entire neutron-flux range with a single fixed-position detector and an output signal that is proportional to only neutron-flux level. No attempt was made to develop the special equipment that would be required for a reactor control-board type installation. Specifications for this type system have been developed, however, and are included in the appendix.

III. THEORY

The system used for this experiment relies upon principles established by others. The theorems of Campbell,¹ as extended by Gwinn and Trenholme² to cover a distribution of pulse amplitudes, are given here as the basic design equations for a mean and mean-square neutron-detection system.

$$E_{dc} = n\bar{q} \int_0^{+\infty} h(t) dt \quad (1)$$

*U.S. Patent 2,903,591.

and

$$E_{\text{rms}} = (E_{\text{rms}})^2 = n\bar{q}^2 \int_0^{+\infty} [h(t)]^2 dt, \quad (2)$$

where

E_{dc} = the mean value of the system response,

n = the average rate of pulse occurrence,

$\bar{q}$ = the mean charge per pulse,

$h(t)$ = the circuit response to a single pulse of unit charge,

E_{ms} = the mean-square value of the system response,

E_{rms} = the root-mean-square value of the system response,

and

$\overline{q^2}$ = the mean-square charge per pulse.

Equation 1 represents the mean output signal from a dc neutron-detection system where the response is directly proportional to the pulse rate and the mean pulse charge. Equation 2 represents the mean-square output signal from a so-called Campbell neutron-detection system, where the measured response, E_{rms} , is proportional to the square root of the product of the pulse rate and the mean-square pulse charge.

This mean charge per pulse is defined as

$$\bar{q} = p_1 q_1 + p_2 q_2 + \dots + p_k q_k = \sum_{k=1}^N p_k q_k. \quad (3)$$

The mean-square charge per pulse is given by

$$\overline{q^2} = p_1 q_1^2 + p_2 q_2^2 + \dots + p_k q_k^2 = \sum_{k=1}^N p_k q_k^2, \quad (4)$$

where

p_k = the probability of obtaining a pulse of charge q_k .

Generally, $(\bar{q})^2 \neq \overline{q^2}$. This will be important later when the system sensitivities are derived.

Before we derive the mean and mean-square voltage-sensitivity equations, we should examine the requirements imposed by the counting portion of the system. Usually two criteria are used to set the system design. First, the system must count accurately at relatively high pulse rates. Second, the system must have the ability to separate the desired pulses from the unwanted ones. These unwanted pulses may be caused by other types of nuclear radiation or may simply be noise. An important property of a counting system is its resolving time, or the minimum time that can elapse between the start of two successive pulses if both are to be counted. The fraction of the counts lost in a counting system can be found from

$$F = n\tau_R e^{-n\tau_R}, \quad (5)$$

where

F = fraction of counts lost,

τ_R = the resolving time,

and

n = the average rate of pulse occurrence.

The resolving time of the system is determined by the combined characteristics of all the circuit elements, including the discriminator level. We will assume for this analysis that the resolving time is determined only by the detector, the preamplifier, and the connecting cable and is defined as the time for the preamplifier output pulse to decay to 36.8% of the peak value. We will further assume that adequate discrimination is achievable and that the statistical variations in both the count rate and mean-square voltage signals can be made acceptable.

Generally for a counting channel, the system components should be selected to minimize the pulse duration so as to improve the resolving time. This desirable feature conflicts with that required for a mean-square voltage system, and compromises have to be made to satisfy both with a single preamplifier. Also, little noise should be generated within the system.

We now consider the equations that describe the detector, cable, and preamplifier. The detector can be represented as a current source, $i(t)$, with internal capacitance. The cable can be considered as a capacitor, equal to the total distributed cable capacitance in parallel with the input impedance of the preamplifier. This is a valid model only if the input impedance of the amplifier is substantially greater than the cable characteristic impedance and the cable is essentially open-circuited. Reflections will occur, but have been shown not to have a significant effect.⁸ The input impedance of the preamplifier is assumed to be resistive. The

preamplifier has clipping and delay time constants, τ_1 and τ_2 , respectively, and an output impedance low enough to eliminate any loading effects.

Fig. 1. Preamplifier Equivalent Circuit

Figure 1 shows the equivalent circuit.

Capacitor C_0 is the sum of the detector and cable capacitance, and R_0 is the input resistance of the preamplifier. The preamplifier transfer function will be assumed to be given by

$$G(s) = \frac{s\bar{G}\omega_2}{(s + \omega_1)(s + \omega_2)}, \quad (6)$$

where

$\bar{G}$ = the midband gain,

$$\omega_1 = 1/\tau_1,$$

$$\omega_2 = 1/\tau_2,$$

τ_1 = clipping time constant,

and

τ_2 = delay time constant.

The mean and mean-square voltage sensitivities will be derived first for the case where there is no preamplifier. The input circuit for this case is a resistor having the same value as that of the input resistance of the preamplifier. For a single current impulse at time $t = 0$, the voltage output is

$$V_i(s) = \frac{q}{C_0(s + \omega_0)}, \quad (7)$$

where

q = the charge of the pulse,

$$\omega_0 = 1/\tau_0,$$

and

τ_0 = input time constant, $R_0 C_0$.

The use of a current impulse assumes that the detector has a negligibly small collection time compared to τ_0 . From Eq. 7,

$$v_1(t) = \frac{q}{C_0} e^{-\omega_0 t}, \quad (8)$$

and from Eqs. 1 and 2,

$$E_{dc} = n\bar{q}R_0 \quad (9)$$

and

$$E_{ms} = (E_{rms})^2 = \frac{n\bar{q}^2 R_0}{2C_0} \quad (10)$$

If the detector collection time is assumed to be equal to τ_e , then a current pulse having a width τ_e and an amplitude $1/\tau_e$ must be used. The voltage output now is

$$V_i(s) = \frac{q(1 - e^{-s\tau_e})}{C_0\tau_e s(s + \omega_0)} \quad (11)$$

and

$$v_i(t) = \frac{qR_0}{\tau_e} \left[\left(1 - e^{-\omega_0 t}\right) u(t) - \left(1 - e^{-\omega_0(t - \tau_e)}\right) u(t - \tau_e) \right] \quad (12)$$

Then from Eqs. 1 and 2,

$$E_{dc} = n\bar{q}R_0 \quad (13)$$

and

$$E_{ms} = (E_{rms})^2 = \frac{n\bar{q}^2 R_0}{2C_0} \left\{ \frac{2\tau_0}{\tau_e} \left[1 - \frac{\tau_0}{\tau_e} \left(1 - e^{-\tau_e/\tau_0} \right) \right] \right\} \quad (14)$$

Comparison of Eqs. 9 and 13 shows that there is no difference in the mean system response if the collection time of the detector is neglected. The mean-square system response is influenced by considering the collection time of the detector, however, as seen by a comparison of Eqs. 10 and 14. The correction needed to the mean-square response if the collection time is ignored, as in Eq. 10, is

$$K_1 = \frac{2\tau_0}{\tau_e} \left[1 - \frac{\tau_0}{\tau_e} \left(1 - e^{-\tau_e/\tau_0} \right) \right] \quad (15)$$

These correction factors have been calculated for several ratios of τ_0/τ_e , as given in Table I.

TABLE I. Collection-time Correction Factors

τ_0/τ_e	K_1
1	0.736
2	0.852
5	0.937
10	0.967

The error introduced by not considering the collection time is generally small, and the collection time is ignored in the remaining derivations, for simplicity. The system sensitivities can be calculated easily from Eqs. 13 and 14.

From Eq. 13,

$$S_{dcn} = k\bar{q}_n \text{ Amps/nv}; \quad (16)$$

From Eq. 14,

$$S_{msn} = \frac{k\bar{q}_n^2 R_0 K_1}{2C_0} \text{ volts}^2/\text{nv}; \quad (17)$$

where

S_{dcn} = the mean-current neutron sensitivity of the detector,

k = the neutron-counting sensitivity, cps/nv,

K_1 = the collection-time correction factor,

S_{msn} = the mean-square voltage neutron sensitivity of the detector-cable-input resistance combination,

$\bar{q}_n$ = the mean charge per neutron pulse,

and

$\bar{q}_n^2$ = the mean-square charge per neutron pulse.

Since S_{dcn} , k , and K_1 are only detector-dependent, they are manufacturer-specified or measurable for a given system. R_0 and C_0 can be easily measured or calculated. In an attempt to find S_{msn} , it is tempting to assume that $(\bar{q}_n)^2 = \bar{q}_n^2$, but this has already been shown to be an untrue assumption. Very little information is presently available as to the value of the mean-square charge, $\bar{q}_n^2$.

We will now consider the system sensitivities when the output of a bandpass preamplifier is measured. Because of the preamplifier bandpass, the mean sensitivity is zero and hence need not be considered. The preamplifier output for a single current impulse at time $t = 0$ is, from Eqs. 6 and 7,

$$V_0(s) = \frac{q\bar{G}\omega_2}{C_0} \left[\frac{s}{(s + \omega_0)(s + \omega_1)(s + \omega_2)} \right] \quad (18)$$

and

$$v_0(t) = qR_0\bar{G}\omega_2 \left[\frac{\omega_2 e^{-\omega_2 t}}{(1 - \omega_2/\omega_0)(\omega_2 - \omega_1)} - \frac{\omega_1 e^{-\omega_1 t}}{(1 - \omega_1/\omega_0)(\omega_2 - \omega_1)} - \frac{e^{-\omega_0 t}}{(1 - \omega_1/\omega_0)(1 - \omega_2/\omega_0)} \right] \quad (19)$$

This equation is valid only if $\omega_1 \neq \omega_0 \neq \omega_2$.

Now, from Eq. 2,

$$\begin{aligned} \overline{E'_{ms}} = (E'_{rms})^2 = \frac{nq^2 R_0 \bar{G}^2}{2C_0} & \left\{ \frac{\omega_2^2}{\omega_0(\omega_2 - \omega_1)} \left\{ \frac{1}{\omega_2 - \omega_1} \left[\frac{\omega_2}{(1 - \omega_2/\omega_0)^2} + \frac{\omega_1}{(1 - \omega_1/\omega_0)^2} - \frac{4\omega_1\omega_2}{(1 - \omega_1/\omega_0)(1 - \omega_2/\omega_0)(\omega_2 + \omega_1)} \right] \right. \right. \\ & \left. \left. + \frac{4}{\omega_0(1 - \omega_2/\omega_0)(1 - \omega_1/\omega_0)} \left[\frac{\omega_2 - \omega_1}{4(1 - \omega_2/\omega_0)(1 - \omega_1/\omega_0)} + \frac{\omega_1}{(1 - \omega_1/\omega_0)(1 + \omega_1/\omega_0)} - \frac{\omega_2}{(1 - \omega_2/\omega_0)(1 + \omega_2/\omega_0)} \right] \right\} \right\} \quad (20) \end{aligned}$$

The mean-square voltage neutron sensitivity at the output of the preamplifier is

$$S'_{msn} = \frac{K_2 \bar{G}^2 k q^2 R_0}{2C_0} \text{ volts}^2/\text{nv}, \quad (21)$$

and

$$S_{msn} = \frac{S'_{msn} K_1}{\bar{G}^2 K_2}, \quad (22)$$

where

S'_{msn} = the mean-square voltage neutron sensitivity as determined at the amplifier output,

and

K_2 = correction factor

$$\begin{aligned} K_2 = \frac{\omega_2^2}{\omega_0(\omega_2 - \omega_1)} & \left\{ \frac{1}{\omega_2 - \omega_1} \left[\frac{\omega_2}{(1 - \omega_2/\omega_0)^2} + \frac{\omega_1}{(1 - \omega_1/\omega_0)^2} - \frac{4\omega_1\omega_2}{(1 - \omega_1/\omega_0)(1 - \omega_2/\omega_0)(\omega_2 + \omega_1)} \right] \right. \\ & \left. + \frac{4}{\omega_0(1 - \omega_2/\omega_0)(1 - \omega_1/\omega_0)} \left[\frac{\omega_2 - \omega_1}{4(1 - \omega_2/\omega_0)(1 - \omega_1/\omega_0)} + \frac{\omega_1}{(1 - \omega_1/\omega_0)(1 + \omega_1/\omega_0)} - \frac{\omega_2}{(1 - \omega_2/\omega_0)(1 + \omega_2/\omega_0)} \right] \right\} \quad (23) \end{aligned}$$

Equation 20 is quite complex, so a simplifying assumption can sometimes be made. Let ω_0 determine the upper half-power breakpoint, or, in other words, make $\omega_2 \gg \omega_0 > \omega_1$. Under these conditions, Eq. 20 reduces to a much simpler expression, or

$$\overline{E}'_{ms} = (E'_{rms})^2 = \frac{nq^2 R_0 \overline{G}^2 \omega_0}{2C_0(\omega_0 + \omega_1)} \quad (24)$$

Therefore,

$$S'_{msn} = \frac{K_3 \overline{G}^2 kq_n^2 R_0}{2C_0} \text{ volts}^2/\text{nv}, \quad (25)$$

and

$$S_{msn} = \frac{S'_{msn} K_1}{\overline{G}^2 K_3}, \quad (26)$$

where

K_3 = correction factor

$$K_3 = \frac{\omega_0}{\omega_0 + \omega_1} \quad (27)$$

The differences between Eqs. 23 and 27 for various ω_2 , ω_0 , and ω_1 have been calculated, and the results are presented in Table II. This table indicates that significant errors can occur when calculating the sensitivity using Eq. 27 even though $\omega_2 = 10\omega_0$.

TABLE II. Correction Factors for Various Preamplifier Characteristics

ω_1	ω_2	K_2	K_3
$0.1\omega_0$	$10\omega_0$	0.818	0.909
$0.1\omega_0$	$5\omega_0$	0.743	0.909
$0.1\omega_0$	$2\omega_0$	0.577	0.909
$0.2\omega_0$	$10\omega_0$	0.743	0.833
$0.2\omega_0$	$5\omega_0$	0.668	0.833
$0.2\omega_0$	$2\omega_0$	0.505	0.833
$0.5\omega_0$	$10\omega_0$	0.577	0.667
$0.5\omega_0$	$5\omega_0$	0.505	0.667
$0.5\omega_0$	$2\omega_0$	0.356	0.667

Equations 10, 13, 14, 20, and 24 can also be used to determine the signal due to either gamma or alpha particles, simply by substituting the appropriate values for the mean or mean-square charge per pulse. The gamma and alpha particle sensitivities can likewise be determined by using Eqs. 16, 17, 22, and 26.

As mentioned earlier, the gamma discrimination in the counting region should present little problem up to gamma fluxes approaching 1×10^7 R/hr. The mean current and mean-square systems ability to discriminate against unwanted pulses have been evaluated by Fowler and Levell.³ From this reference, the mean current signal is 10% higher than the value due to the neutron flux alone when

$$\frac{N_{\alpha} \bar{q}_{\alpha} + N_{\beta} \bar{q}_{\beta}}{N_n \bar{q}_n} = 0.1 \quad (28)$$

and

$$\phi_{dcn} = \frac{N_{\alpha} \bar{q}_{\alpha} + N_{\beta} \bar{q}_{\beta}}{0.1 k \bar{q}_n}, \quad (29)$$

where

N_{α} = the number of pulses due to alpha particles,

N_{β} = the number of pulses due to prompt betas caused by gamma rays,

and

ϕ_{dcn} = the neutron flux at which the 10% error in the dc signal occurs.

Also from Ref. 3, the mean-square voltage signal is 10% higher than the value due to the neutron flux alone when

$$\frac{N_{\alpha} \bar{q}_{\alpha}^2 + N_{\beta} \bar{q}_{\beta}^2}{N_n \bar{q}_n^2} = 0.1 \quad (30)$$

and

$$\phi_{nms} = \frac{N_{\alpha} \bar{q}_{\alpha}^2 + N_{\beta} \bar{q}_{\beta}^2}{0.1 k \bar{q}_n^2}, \quad (31)$$

where

ϕ_{nms} = the neutron flux at which the 10% error in the mean-square signal occurs.

If we now assume that there is a negligible gamma flux, the lowest neutron flux detectable with a 10% error will be determined by the coating alpha particles alone. From Eqs. 29 and 31 and typical values for N_{α} , $\bar{q}_{\alpha}^2$, $\bar{q}_n^2$, and k ,

$$\phi_{dcn} = 7 \times 10^5 \text{ nv.}$$

and

$$\phi_{nms} = 2 \times 10^4 \text{ nv.}$$

From the above, a 35:1 improvement in neutron-flux measurement capability can be expected from a mean-square voltage system when the lower limitation is determined by the coating alpha particles.

If another 10% error due to the gamma flux is also allowed (20% total error), the gamma flux necessary is

$$\phi_{dc\gamma} = 2 \times 10^2 \text{ R/hr}$$

and

$$\phi_{ms\gamma} = 4 \times 10^4 \text{ R/hr.}$$

Here a 200:1 improvement in gamma discrimination is realized when a mean-square system is used.

The fractional standard deviations in both the counting and mean-square voltage signals at constant neutron flux have not been considered here as design criteria. These signal variations must be minimized, of course, consistent with adequate sensitivity and response time. This must be done to reduce false reactor period trip signals arising from these variations.

Others⁸ have shown that if Eq. 24 describes the system, and further if T , the averaging time of the final integrating circuit, is much greater than $1/\omega_1$, then the standard deviation of the mean-square voltage signal is given by

$$D = \left[\frac{1}{T(\omega_0 + \omega_1)} + \frac{1}{2k\Phi T} \right]^{1/2}, \quad (32)$$

where

D = fractional standard deviation,

T = the averaging time of the final integrating circuit,

and

Φ = the constant neutron flux.

This equation is claimed to be accurate to within 5% if $T \geq 10\tau_1$. As Φ , the neutron flux, increases so that $2k\Phi > \omega_0 + \omega_1$, then the fractional standard deviation approaches a constant that is determined completely by T , ω_0 , and ω_1 .

The fractional standard deviation of the counting portion of the system is determined by circuitry other than that considered here. It has been analyzed by others, and suitable circuitry is presently available such that false reactor shutdowns are minimized.

IV. SYSTEM DESIGN

Several factors had to be considered in the design of a preamplifier capable of both counting and operating in the mean-square voltage mode. First to be considered was the pulse-resolving time, which determines the highest achievable counting rate of the system. The resolving time was defined as the time required for a preamplifier pulse to decrease to 36.8% of the peak value. This definition is quite arbitrary and depends upon the pulse-height-discriminator setting. The resolving time of the system, as stated before, was also assumed to be completely determined by the preamplifier, cable, and detector. The output pulse shape and resolving time can be determined from Eq. 19 if the system characteristics are given. Figure 2 shows several typical pulse shapes. Then from Eq. 5, the counting loss can be calculated at any given counting rate and hence neutron flux.

Fig. 2. Preamplifier Output Neutron-pulse Shapes

For an optimum counting system, the chamber-signal cable should be terminated in its characteristic impedance at the preamplifier. If this is done, the cable is essentially a lossless transmission line and the pulses are transmitted from the chamber to the preamplifier essentially unaltered in shape. With a suitable preamplifier bandwidth, resolving times are determined almost entirely by the collection time of the chamber. For an out-of-core chamber, counting rates up to 1×10^5 counts per second (cps) can be measured very accurately ($<1\%$) and up to 1×10^6 cps with about a 20% maximum counting loss. With the signal cable terminated, the mean-square voltage sensitivity is $\sim 3.6 \times 10^{-16}$ volts²/nv as calculated from Eq. 17, when R_0 is 70 ohms, C_0 , the detector capacity only, is 140 pF for an out-of-core chamber, k is 1.43 cps/nv, K_1 is 0.1, and q_n^2 is $\sim 6.5 \times 10^{-27}$ coulombs². Even at neutron fluxes as high as 1×10^5 nv (1.4×10^5 cps), the calculated E_{rmsn} at the preamplifier input is only $6 \mu\text{V}$ and is about equivalent to the system amplifier noise referred to the input.

To increase the mean-square voltage sensitivity, the input impedance of the preamplifier must be increased, but when this is done, the signal cable becomes mismatched. Now the cable capacity, as mentioned earlier, acts as a lumped capacitor across the preamplifier input. A low-capacitance-per-foot type signal cable, such as RG-114/U (6.5 pF/ft), should be considered so as not to reduce the sensitivity by increasing C_0 . The resolving time must now be made longer, and this limits the highest achievable counting rate.

As a compromise, the system designed for this experiment allowed the resolving time to increase to $\sim 1.3 \mu\text{sec}$, resulting in a 20% counting loss at 2×10^5 cps. The mean-square voltage sensitivity was calculated to produce a usable signal above the system noise at $\sim 5 \times 10^3$ nv by selecting R_0 as 3.7 K or 20 times the RG-114/U cable characteristic impedance of 185 ohms. The detector-cable capacitance, C_0 , would be 330 or 660 pF, depending upon the cable lengths. The calculated E_{rms} at the preamplifier input using Eq. 14 was $14 \mu\text{V}$ for the short cable and $10 \mu\text{V}$ for the long cable for the stated flux level. The resolving time is little affected by cable length and is determined by the clipping time constant of the preamplifier. The mean-square voltage sensitivity is controlled essentially by the input time constant $\tau_0(R_0C_0)$.

V. SYSTEM DESCRIPTION

The system to be described is capable of covering the neutron-flux range from 1 to 10^{10} nv with a single fixed-position detector in the presence of large gamma fluxes. Counting and mean-square voltage channels operating from a single pulse-shaping preamplifier were used in parallel. The preamplifier characteristics were not modified by switching, nor was the operating voltage applied to the detector changed. An output signal that is

proportional to the neutron flux is available over the entire operating neutron-flux range. Figure 3 is a block diagram of the system. More

Fig. 3. System Block Diagram

sophisticated electronics would be necessary if the system were to be installed as an operation instrument in a reactor, but were deemed unnecessary for this experiment.

A. Detector

The detector used for this experiment was a standard, unguarded Westinghouse WL-6376 fission counter

operating with 300 volts dc applied. This voltage was sufficient to operate the detector on the flat portion of the saturation curves in both the direct current and mean-square voltage modes up to neutron-flux levels of 2×10^9 nv, the highest attainable during the experiment. The applied voltage was at this flux level, increased up to 600 volts without changing any of the system sensitivities.

B. Connecting Cable

The connecting cable, because of its distributed capacitance, had a controlling effect on the mean-square voltage channel performance. To provide an adequate mean-square voltage sensitivity, an RG-114/U low-capacitance-per-foot type cable was used between the detector and the preamplifier. To demonstrate the dependence of the system performance on this cable, lengths of 23.5 and 78.5 ft were used in the experiment. These cable lengths were selected to approximately double the total input capacity, C_0 , and are believed to represent the length limits needed for a prototype system.

C. Preamplifier

The preamplifier characteristics were selected on the basis of design criteria set forth in Section III above. The following parameters define one set of preamplifier characteristics:

$$\omega_1 = 3 \times 10^5 \text{ rad/sec,}$$

$$\omega_2 = 5 \times 10^6 \text{ rad/sec,}$$

$$R_0 = 3.7 \times 10^3 \text{ ohms,}$$

$$C_0 = (1.4 + 0.065L) \times 10^{-10} \text{ Farads}$$

$L = \text{RG-114/U cable length in feet,}$

$$\omega_0 = \frac{1}{R_0 C_0},$$

and

$$\bar{G} = \sim 300.$$

The output noise level was to be less than the α signal component from the chamber ($< 6 \mu\text{V}$ referred to the input).

D. Root-mean-square Voltmeter

The rms voltmeter used was a Hewlett-Packard (HP) Model 3400A, having 12 ranges from 0.001 to 300 volts. The effective final integrating time constant, T , for this type of meter is approximately 0.4 sec.

E. Pulse Amplifier, Discriminator, and Count Rate Meter

The pulse amplifier and discriminator consisted of a modified Atomic Instrument Company Model 218 instrument. The output of this instrument was connected to a modified Argonne-built Model CRM 5E count rate meter having ten ranges from 20 to 2×10^5 cps full scale, as well as a logarithmic range.

F. Average Magnitude Voltmeter

The average magnitude voltmeter was a HP Model 400-C with 12 ranges from 0.001 to 300 volts full scale.

G. Picoammeter

The picoammeter used was a standard Keithley Model 410 instrument with current ranges from 1×10^{-3} to 1×10^{-14} amperes.

H. Power Supply

The power supply selected was a Northeast Scientific Corporation Model RE-1603 having a voltage range of 300 to 1600 volts. This power supply was isolated above the system ground. To eliminate low-frequency power-supply noise in the mean-current instrument at low flux levels, a battery supply was occasionally used.

VI. RESULTS

The results of this experiment are presented in three sections. Section A gives the experimental responses of the designed system. Section B is devoted to the experimental determination of basic pulse parameters, and Section C compares the theoretically predicted responses to the measured values when the experimentally determined pulse parameters are used in the calculations.

A. Experimental System Responses

Figure 4 shows the complete system response to neutron flux and indicates about a 1.5-decade overlap between the count-rate and rms

Fig. 4. System Response to Neutron Flux

Figure 5 shows the effect of two different cable lengths on the rms sensitivity. The 327-pF capacity represents the chamber plus 23.5 ft of RG-114/U cable; the 655-pF capacity is the chamber plus 78.5 ft of the same cable.

Gwinn and Trenholme² have shown that at large pulse rates the average-magnitude voltage signal squared is related to the mean-square signal by a constant, $2/\pi$ (0.637). To verify this result experimentally, data were taken with an average-magnitude and true-rms voltmeter simultaneously. Figure 6 shows the difference between these two fluctuating signals. At large pulse rates, the two signals are related by a constant (0.542), which is close to the theoretically predicted value. The response of the average-magnitude signal at small pulse rates is rather unusual. The behavior in this range could be due to the pulse statistics changing from essentially Gaussian to Poisson.

signals. The range of overlap between the counting and rms channels is based on a 20% counting loss at the high end of the counting channel and a 20% "noise" component at the low end of the rms channel. These errors would not be detectable when a seven-decade Log Count Rate Meter or an RMS Log-N-Period instrument was used. The use of these two seven-decade instruments can provide ten decades of neutron-flux coverage with adequate overlap. Only the mean-current system was affected by the largest gamma flux of 1.5×10^3 R/hr encountered at low neutron flux.

Fig. 5. Mean-square Voltage Output for Different Signal Cable Lengths

Fig. 6

Comparison of Mean-square and Average-magnitude-square Voltage Output

B. Basic Pulse Parameters

1. Chamber-coating Alpha-parameter Determinations

The number of alpha pulses produced by the uranium coating isotopes can be theoretically predicted by

$$N_{\alpha} = N_{U^{238}} + N_{U^{234}} + N_{U^{235}}, \quad (33)$$

where

$$N_{U^{238}} = 12.3W \text{ pps},$$

$$N_{U^{234}} = 2.27 \times 10^5 W \text{ pps},$$

$$N_{U^{235}} = 78.5W \text{ pps},$$

and

W = total weight of each isotope presented in the coating.

The chamber used for these measurements had a total uranium content of 1840 mg, 1720 mg being U^{235} . The U^{238} contributes very little to the total alpha pulse rate and will not be considered. Now if we assume that 5% of the uranium not U^{235} is U^{234} , the $N_{U^{234}} = 1.43 \times 10^6$ pps. The U^{235} pulse rate, $N_{U^{235}} = 1.35 \times 10^6$ pps, and

$$N_{\alpha} = 1.56 \times 10^6 \text{ pps}.$$

The alpha pulse rate is almost completely determined by the U^{234} content. Any reduction in the amount of U^{234} present in the uranium coating will improve the performance of the system by reducing the alpha mean current and mean-square voltage. Thin internal shields over the fissionable material would also reduce the alpha component.

Fig. 7. Integral Bias Response to Alpha and Neutron Pulses

The number of alpha particles emanated by the fission-chamber coating was experimentally determined in two different ways. The first method extrapolated the integral bias response curve to alpha pulses, shown in Fig. 7, to zero discriminator voltage. By this technique, an average alpha pulse rate (N_α) of 1.4×10^6 pulses per second (pps) was obtained. The alpha pulses shown on an oscilloscope were then photographed. The average number of pulses counted on the picture for a given time interval yielded an N_α of 1.3×10^6 pps. Thus there is excellent agreement between the experimental results and the theoretically predicted value. Hereinafter, $N_\alpha = 1.3 \times 10^6$ will be the accepted value.

The mean charge per alpha pulse was experimentally determined by two different methods. First, the mean alpha current ($I_{dc\alpha}$) from the chamber was measured (1.18×10^{-8} amperes). The mean charge can then be calculated by

$$\bar{q}_\alpha = \frac{I_{dc\alpha}}{N_\alpha} = \frac{1.18 \times 10^{-8}}{1.3 \times 10^6} = 9.1 \times 10^{-15} \text{ coulombs/pulse.}$$

By the use of Eq. 12, the average charge, $\bar{q}_\alpha$, should be 1.1×10^{-14} coulombs/pulse in order to reproduce the average pulse shape shown by the oscilloscope photographs. A value of 1×10^{-14} coulombs/pulse is given by Fowler and Levell,³ and because it was experimentally verified, it will hereinafter be considered the accepted value.

The mean-square charge per alpha pulse was experimentally determined by measuring the voltage, $E_{rms\alpha}$, at the preamplifier output and then using Eq. 20 to calculate the charge. The rms alpha voltage was measured for each of the two cables used during the experiment. Hence two values of C_0 could be considered, and the mean-square charge was independently determined twice from

$$\bar{q}_\alpha^2 = \frac{2E_{rms}C_0}{N_\alpha R_0 G^2 K_2} \quad (34)$$

The following values were determined:

$$\bar{q}_{\alpha 1}^2 = 3.6 \times 10^{-30} \text{ coulombs}^2/\text{pulse from the short cable,}$$

and

$$\bar{q}_{\alpha 2}^2 = 4.3 \times 10^{-30} \text{ coulombs}^2/\text{pulse from the long cable.}$$

Hereafter, $\overline{q_\alpha^2} = 4 \times 10^{-30}$ coulombs²/pulse will be the accepted value and will be used in the calculations.

2. Neutron Parameter Determinations

The number of pulses produced by a given fission chamber per unit neutron flux can be theoretically predicted from

$$N_n = \frac{N_a \sigma_f W E}{1000 A} \text{ pps/nv}, \quad (35)$$

where

N_n = number of pulses produced per unit flux,

N_a = Avogadro number (6.02×10^{23}),

σ_f = fission cross section in barns,

W = weight in milligrams of fissionable material,

A = atomic weight of fissionable isotope,

and

E = the counting efficiency.

For the fission chamber considered in these experiments,

$W = 1720$ mg of U^{235}

and

$E = 0.59$ from Ref 9.

Therefore,

$$N_n = k = 1.43 \text{ pps/nv}.$$

This number was experimentally checked by extrapolating the integral bias-response curve to neutron pulses, shown in Fig. 7, to zero discriminator voltage. By this technique, a counting sensitivity of 1.54 pps/nv is obtained when all the pulses are counted. This is in good agreement with the theoretical value. The theoretical prediction of N_n was used in all calculations.

The mean charge per neutron pulse was determined in two different ways. First, the mean neutron current (I_{dcn}) was measured at a known neutron flux, and the charge determined by

$$\overline{q_n} = \frac{I_{dcn}}{N_n} = \frac{1.85 \times 10^{-13}}{1.43} = 1.29 \times 10^{-13} \text{ coulombs/pulse.}$$

The second method consisted of photographing the neutron pulses displayed on an oscilloscope and by using Eq. 19 to determine the average charge necessary to reproduce the average pulse shape. Using this method, we determined the following values for the two different cables used in the experiment:

$$\overline{q_n} = 1.45 \times 10^{-13} \text{ coulombs/pulse from the short cable;}$$

$$\overline{q_n} = 1.50 \times 10^{-13} \text{ coulombs/pulse from the long cable.}$$

This is in good agreement with the charge measured by the first technique and the value of 1.5×10^{-13} coulombs reported by Ref. 3. A charge $\overline{q_n}$ of 1.4×10^{-13} coulombs/pulse was used in all calculations.

The mean-square charge per neutron pulse was experimentally determined by measuring the voltage, E_{rmsn} , at a given neutron-flux level and then by using Eq. 9 to determine the value. From Eq. 9,

$$\overline{q_n^2} = \frac{2C_0(E_{rmsn})^2}{N_n R_0 K_1}. \quad (36)$$

The following values were determined from measurements taken with two different cable lengths and hence capacitances:

$$\overline{q_n^2} = 6.37 \times 10^{-27} \text{ coulombs}^2/\text{pulse from the short cable;}$$

$$\overline{q_n^2} = 6.59 \times 10^{-27} \text{ coulombs}^2/\text{pulse from the long cable.}$$

A value of 6.5×10^{-27} coulombs²/pulse was used in all the calculations.

C. Comparison of Theoretical and Experimental Responses

1. Neutron-pulse Collection Time

In a fission chamber, the highly charged fragments produce a typical track that extends across the entire plate spacing or gas gap. After this track is produced, the resultant ions and electrons drift toward the electrodes. If the clipping time constant of the preamplifier or input circuit is made large, compared with the time for collection of the electrons, but small compared with ions, the pulse response is due to only the electron motion, and the pulse-collection time can be calculated as

$$\tau_e = \frac{d}{V_e}, \quad (37)$$

where

τ_e is the collection time in seconds,

d is the chamber plate spacing in cm,

and

V_e is the electron drift velocity in cm/sec.

V_e is a function of the field strength, E , and the internal pressure, p , of the gas used. The dependence of V_e on E/p is discussed in Ref. 10. For the fission chamber used in this experiment, the collection time was calculated to be 0.16×10^{-6} sec for a drift velocity of 2×10^6 cm/sec in argon-nitrogen with 300 volts applied and a plate spacing of 0.32 cm.

To verify that the magnitude of the calculated collection time was correct, and to further prove that Eq. 12 truly represents the actual pulse shape produced by the fission chamber used in these experiments, oscilloscope photographs were taken of the pulses. A typical pulse across the input resistor R_0 of Fig. 1 is shown in Fig. 8. From these photographs,

$0.2 \mu \text{ sec/div}$, 0.5 mv/div

$1 \mu \text{ sec/div}$, 0.5 mv/div

$R_0 = 19.4 \text{ K}$ $C_0 = 195 \text{ pf}$

EXPERIMENTAL

$R_0 = 19.4 \text{ K}$ $C_0 = 195 \text{ pf}$ $\tau_e = 0.15 \mu \text{ sec}$ $\bar{q}_n = 1.4 \times 10^{-13} \text{ COULOMBS/PULSE}$

THEORETICAL

Fig. 8. Comparison of Experimental and Theoretical (Eq. 12) Input-circuit Neutron-pulse Shape (No Preamplifier)

the average collection time was found to be $0.15 \mu\text{sec}$. Figure 8 also compares the pulse shape calculated from Eq. 12 to the experimental data. Both the pulse-collection time and shape measured agree very well with the theoretically predicted values.

2. Neutron-pulse Shape at Preamplifier Input

To verify that the pulse shape at the input of the preamplifier could also be predicted by Eq. 12, to prove that the input impedance was essentially resistive, oscilloscope photographs of the pulse shape at the preamplifier input were taken and are shown in Fig. 9. The reflections produced because the cable is unterminated can be seen in this figure as predicted. Figure 9 also compares the pulse shape predicted by Eq. 12 to the experimental data, and excellent agreement is shown.

Fig. 9. Comparison of Experimental and Theoretical (Eq. 12) Preamplifier-input Neutron-pulse Shape

3. Neutron-pulse Shape at Preamplifier Output

The pulse shape at the preamplifier output was predicted by Eq. 19 when the collection time was ignored. To prove that this assumption

is valid, photographs of the preamplifier output pulse shape are shown in Fig. 10 and compared to Eq. 19. Again there is excellent agreement. The reflections produced by the unterminated cable are almost completely removed by the preamplifier characteristics.

Fig. 10. Comparison of Experimental and Theoretical (Eq. 19) Preamplifier-output Neutron-pulse Shape

4. Mean-square Voltage Neutron Sensitivity

The final and most significant point is to show whether Campbell's theorem is in fact valid, that is, to see how the predicted sensitivity given by Eq. 21 compares with the experimental values.

The predicted sensitivity using Eq. 21 is

$$2.90 \times 10^{-9} \text{ volts}^2/\text{nv} \text{ for the short cable}$$

and

$$1.41 \times 10^{-9} \text{ volts}^2/\text{nv} \text{ for the long cable,}$$

where the constants used are

$$k = 1.43 \text{ pps/nv},$$

$$\overline{q_n^2} = 6.5 \times 10^{-27} \text{ coulombs}^2/\text{pulse},$$

$$R_0 = 3.7 \times 10^3 \text{ ohms},$$

and

$$\overline{G} = 292.$$

For the short cable,

$$C_0 = 327 \text{ pF and } K_2 = 0.648;$$

for the long cable,

$$C_0 = 655 \text{ pF and } K_2 = 0.632.$$

The measured sensitivities were

$$3.1 \times 10^{-9} \text{ volts}^2/\text{nv for the short cable},$$

and

$$1.6 \times 10^{-9} \text{ volts}^2/\text{nv for the long cable}.$$

The predicted and measured responses agree well, and the discrepancy can easily be accounted for in the determined values for either k or $\overline{q_n^2}$.

VII. RESULTS AND CONCLUSIONS

In general, the theoretical predictions made are in excellent agreement with the experimental results. Further, the detection system designed and tested has monitored ten decades of reactor flux with a single fixed-position detector. No change in the amplifier characteristics or detector excitation voltage was necessary over the entire range of neutron flux. The excellent gamma discrimination claimed for a mean-square system has not yet been completely verified, but has been shown to be better than a mean-current system.

The unusual behavior of the average-magnitude signal response in the low neutron-flux range makes it unwise at this time to use this measurement in place of a true rms signal. The gamma discrimination of an average

magnitude system is not known to have been theoretically predicted, and the improvement, if any, gained over a mean-current system, is questionable.

A mean-square neutron-detection system should show particular promise when applied to fast reactors such as the EBR-II and the Fast Flux Test Facility (FFTF). This system also appears to be relatively attractive from a reliability and economy standpoint when applied to a reactor such as AARR.

VIII. RECOMMENDATIONS FOR FUTURE WORK

A. EBR-II Test of the Present System

Even though the present wide-range monitoring system is rather crudely assembled, it should be tested in EBR-II as soon as possible. If EBR-II were used for a reactor test, data from a mean-square voltage channel would be taken for the first time during reactor operation at low neutron flux and high gamma background. A test of this type might once and for all verify the excellent gamma discrimination claimed for a mean-square voltage channel in the low neutron-flux region.

B. True Mean-square Voltage Signal vs. Average-magnitude-square Signal Gamma Discrimination

There is some doubt as to whether sufficient, or in fact any, gamma discrimination is achieved when the average magnitude value of the fluctuating signal is displayed instead of the true mean-square value of the signal. The above system and test would be used to show the differences, if any:

C. Reactor-prototype System

A reactor-prototype wide-range neutron-flux monitoring system should be immediately purchased based on the specifications in the appendix. This prototype system should also be tested in EBR-II so that performance and reliability can be evaluated. The results of this evaluation would be of considerable value when similar instruments are applied to reactors such as EBR-II, AARR, and even perhaps FFTF.

D. Establishment of Standards for Mean-square Voltage Channel

Because of the many variables, such as cable type and length and preamplifier characteristics, which ultimately determine the mean-square voltage channel neutron sensitivity, some attempt should be made to establish standards for this type system. These standards would allow the instrument engineer to apply the mean-square system as easily as the

more conventional mean-current systems to new reactor designs. This is not possible at present.

E. Reduction of Alpha Voltage Component

In many reactors, the lower limit of neutron detection for a mean-square voltage channel will be set by the alpha component from the fissionable material in the chamber itself. Techniques such as internal shielding of the fissionable material coating or fissionable isotopic material selection should be investigated in an attempt to reduce the alpha component of voltage. A wider range of neutron monitoring and greater overlap will be achievable if the alpha component can be reduced.

F. RMS Log-N-Period Channel

An RMS Log-N-Period Channel is not known to exist commercially. Further research and development must be devoted to investigating applicable techniques and evaluating circuit designs. This instrument is very necessary for a reactor prototype system.

APPENDIX

Design and Performance Specification for a Wide-range
Neutron-monitoring System (March 1966)

I. GeneralA. Design Criteria

The instruments shall be constructed of components selected on the basis of insuring quality, reliability, maintainability, performance, and long life. Solid-state components should be used throughout, with the exception of detector and/or electrometer tubes where necessary. Field-proven circuit designs shall be used when possible. The only controls that can be located on the front panel of each instrument are those that check the operation or calibration of the instrument or those that change range. All front-panel switches shall be of the rotary type with positive detents. Pushbuttons and toggle switches cannot be used.

B. Operating Conditions

Each instrument shall be designed to give satisfactory performance when operated over the following conditions:

<u>Parameter</u>	<u>Units</u>	<u>Minimum</u>	<u>Maximum</u>	<u>Design Average</u>
Temperature	°C	10	50	30
Relative Humidity	%	10	90	50
Input Power, 60-Hz	Volts	105	129	117

C. Brief Description of Instrument

A single fission counter/chamber detector shall be used to monitor continuously neutron fluxes from 1 to 1×10^{10} nv without changing its position, remote-amplifier characteristics, or operating voltage. The detector sensitivity shall be at least 0.4 cps/nv, when used as a fission counter, and shall operate over the range from 1.0 to 3.0×10^5 nv. A single high-voltage power supply shall provide the polarizing voltage for the detector. A non-switched remote amplifier shall be provided. The remote amplifier shall be connected to a log-count-rate indicator that will cover the range from 0.1 to 10^6 cps. Period indication from -30 to infinity to +3 sec shall be included over this range. A pulse-height discriminator shall reject noise pulses, and a built-in count rate and period-calibrator circuit for alignment and testing shall be provided, along with suitable trip circuits for annunciation and control.

The same detector shall have adequate sensitivity to operate in the mean-square voltage mode over the range of $5.0 \times 10^3 \times 1.0$ to 10^{10} nv. A log power indicator covering seven decades up to 150% power at 10^{10} nv and period indication from -30 to infinity to +3 sec shall also be connected to the remote amplifier. A built-in power and period calibration circuit for alignment and testing shall be provided, along with suitable trip circuits for annunciation and control.

The detector output shall be simultaneously connected directly to a mean current amplifier to indicate 0-125% power with $\sim 1 \times 10^{-3}$ amperes input current at full scale (125% indication) at a neutron flux of 10^{10} nv. A built-in calibration circuit for alignment and testing shall be provided, along with suitable trip circuits for annunciation and control.

II. Instrument Specifications

A. Detector: Fission Counter/Chamber

1.0 Dimensions

- 1.1 Sensitive Length: $9\frac{1}{4}$ in.
- 1.2 Overall Length: $13\frac{1}{2}$ in.
- 1.3 Diameter (Maximum): $3\frac{1}{16}$ in.

2.0 Weight

- 2.1 Net Weight: 5 lb
- 2.2 Shipping Weight: 11 lb
- 2.3 U^{235} Contained Weight: 1.5 g

3.0 Materials

- 3.1 Shell and Electrodes: AA1100 Aluminum
- 3.2 Insulators: Mica and alumina
- 3.3 Electrode Coating: U_3O_8 90% U^{235} enriched
- 3.4 Connectors: Two to mate with HN type for high voltage and collector. They are to be aluminum and removable.
- 3.5 Filling Gas: Argon and nitrogen (at 1 atm)

4.0 Operating Characteristics

- 4.1 Insulation Resistance of Either Connector (To Ground): 10^{12} ohms at 25°C with 500 V dc applied
- 4.2 Voltage Maximum: 1000 Vdc
- 4.3 Capacity: 140 pF
- 4.4 As a Counter
 - 4.4.1 Operating Voltage: 500 Vdc
 - 4.4.2 Operating Voltage Plateau: 200 to 800 Vdc
 - 4.4.3 Neutron-flux Range: 1.0 to 2.5×10^5 nv
 - 4.4.4 Neutron Sensitivity (No Gamma): ~ 0.70 cps/nv
 2×10^5 R/hr ~ 0.66 cps/nv

- 4.4.5 Output Pulse Characteristics
 - 4.4.5.1 Magnitude: * $\sim 100 \mu V$
 - 4.4.5.2 Rise Time: $\sim 0.2 \mu sec$
- 4.5 As a Mean-square Voltage Detector
 - 4.5.1 Operating Voltage: 500 V dc
 - 4.5.2 Operating Voltage Range: 300 to 800 V dc
 - 4.5.3 Neutron-flux Range: 1.0×10^3 to 1.0×10^{10} nv
 - 4.5.4 Neutron Sensitivity (No Gamma): * $> 3.0 \times 10^{-14} \langle V^2 \rangle / nv$
 - 4.5.5 Gamma Sensitivity: * $< 3.0 \times 10^{-13} \langle V^2 \rangle R/hr$
- 4.6 As a Mean Current Detector
 - 4.6.1 Operating Voltage: 500 V dc
 - 4.6.2 Operating Voltage Range: 300 to 800 V dc
 - 4.6.3 Neutron Flux Range: 5×10^5 to 1.0×10^{10} nv
 - 4.6.4 Neutron Sensitivity: $\sim 1.4 \times 10^{-13}$ Amps/nv
 - 4.6.5 Gamma Sensitivity: $\sim 2.2 \times 10^{-11}$ Amps/R/hr
 - 4.6.6 Alpha Current: $\sim 8 \times 10^{-9}$ Amps
- 5.0 Environmental Conditions
 - 5.1 Temperature (Maximum): 300°C
 - 5.2 Life (Neutron Exposure): 10^{19} nvt for 10% reduction in sensitivity
 - 5.3 Pressure: 50 psig
 - 5.4 Vibration: Designed to operate under conditions of MIL-STD-167
 - 5.5 Shock: Designed to operate after application per MIL-S-901B

B. Remote Amplifier

- 1.0 Input Impedance: 5000 ohms
- 2.0 Input Pulse: Positive
- 3.0 Output Impedance: 35 ohms or matched to interconnecting cable
- 4.0 Gain: 200 to 400, adjustable in steps of 50
- 5.0 Noise
 - 5.1 Detector Connected; High-voltage Supply Off: $< 7.0 \mu V$ rms, referred to input
 - 5.2 Detector Connected; High-voltage Supply on at -600 V dc
(α Limit): $< 10 \mu V$ rms referred to input
- 6.0 Linearity: $\pm 1\%$, 0-18 V peak-to-peak output
- 7.0 Bandwidth: 50 to 750 kHz
- 8.0 Stability: $< \pm 2\%$ from all causes
- 9.0 Drift: $< \pm 0.5\%$ per day

*At remote amplifier input.

10.0 Power Requirements: The power for the remote amplifier shall be supplied from the Intermediate Range Monitor

11.0 Cable

11.1 Input: The cable between the detector collector and the remote amplifier shall be RG-114/U up to 80 ft long

11.2 Output: The cable between the remote amplifier and the Source and Intermediate Range Monitors shall be RG-71/U up to 400 ft long

C. Source Range Monitor

1.0 Log Count Rate Meter

1.1 Range: 0.1 to 10^6 cps

1.2 Meter Scale: 10^{-1} to 10^6 counts per second, logarithmic in seven decades

1.3 Accuracy: The observed count rate shall not deviate from the true count rate by more than $\pm 2.0\%$ of equivalent linear, full-scale, recorder-output voltage over the top six decades and by more than $\pm 5\%$ over the bottom decade under the combined variations of temperature, humidity, and line voltage.

1.4 Counting Loss: Not more than 20% counting loss shall occur at 1×10^6 cps random input signal.

1.5 Drift: Not more than $\pm 1\%$ of full scale in 100 hr under the combined variations of temperature, humidity, and line voltage

1.6 Rate Meter Response Time: The time constant (0-63%) of the log count rate meter to a positive step no greater than 50% at any count rate shall not be beyond the limits shown in the following table:

<u>Rate Change, cps</u>	<u>Response Time, sec</u>
0.1 to 0.2	40 ± 10
1.0 to 2.0	18 ± 6
10 to 20	1.8 ± 0.2
100 to 200	0.18 ± 0.02
1000 to 2000	0.018 ± 0.002
Higher	$< 0.018 \pm 0.002$

1.7 Sensitivity: A 15-mV negative-step-input signal through a 10-pF capacitor shall produce a count at the output

1.8 Sensitivity Adjustment: An attenuator shall allow adjustments of the input sensitivity over a range from 1:1 to 8:1 in four steps.

1.9 Discriminator: Discrimination of negative-step-input signals with amplitudes between 15 and 300 mV applied through a 10-pF capacitor with sensitivity attenuator at minimum shall be possible

- 1.10 Calibration: A built-in calibrator shall provide two calibration signals of 10 and 10^5 cps. The observed count rate of the calibrator shall not deviate from the true count rate by more than $\pm 1\%$ at 10^5 cps and $\pm 2\%$ at 10 cps under the combined variations of temperature, humidity, and line voltage.
- 1.11 Outputs
 - 1.11.1 Recorder Output: 0 to 10 mV dc
 - 1.11.2 Meter Output: G.E. DB-40, taut band, 1%, 7.1-in. scale or equivalent chassis mounted. A 0-1 mA full-scale signal shall also be available for driving a remote meter.
 - 1.11.3 Scaler Output: Positive pulses of 0.5 μ sec or faster rise time and at least 1 V in magnitude are available
- 2.0 Period Meter
 - 2.1 Range: -30 to infinity to +3 sec
 - 2.2 Meter Scale: Period-Seconds -30 to infinity to +3 (Hyperbolic Scale)
 - 2.3 Accuracy: The observed period shall not deviate from the true period by more than $\pm 2\%$ of equivalent, full-scale, recorded output voltage under the combined variation of temperature, humidity, and line voltage
 - 2.4 Drift: Not more than $\pm 1\%$ of full scale in 100 hr under the combined variation of temperature, humidity, and line voltage.
 - 2.5 Period Meter Response Time: The time constant (0-63%) to a ramp input at any given signal level above 10 cps shall be 1.5 sec $\pm 20\%$. The period meter shall not respond to signals less than 10 cps.
 - 2.6 Calibration: A built-in calibrator shall provide a fixed, full-scale calibration signal. The accuracy of the calibrator shall be within $\pm 1\%$ under the combined variation of temperature, humidity, and line voltage. An adjustable ramp signal shall also be available to check the meter at intermediate values.
 - 2.7 Outputs
 - 2.7.1 Recorder Output: 0 to 10 mV dc
 - 2.7.2 Meter Output: G.E. DB-40, taut band 1%, 7.1-in. scale or equivalent chassis-mounted. A 0-1 mA full-scale signal shall also be available for driving a remote meter.
- 3.0 Trip Circuits: Two types of trip outputs shall be provided for each trip function
 - 3.1 Requirements
 - 3.1.1 Annunciator Output: The untripped output shall be 20 V dc at 50 mA and 0 V dc when tripped and latched

- 3.1.2 Safety System Output: The untripped output shall be 12 V dc at 25 mA and 0 V dc when tripped and latched
- 3.1.3 Reproducibility: $\pm 1/2\%$ of full-scale input
- 3.1.4 Hysteresis: 1% of full-scale input
- 3.1.5 Response Time: 3 ± 0.5 msec
- 3.1.6 Drift: Less than $\pm 1\%$ full scale per 100 hr under combined variation of temperature, humidity, and line voltage
- 3.1.7 Trip Set: 2-100% full scale, adjustable
- 3.1.8 Trip Reset: Manual switch on front panel
- 3.1.9 Trip Indication: Light on front panel of instrument shall indicate and identify each trip function
- 3.2 Trip Function: Two shall be provided
 - 3.2.1 Chassis Interlock: If the chassis is removed from the drawer, or the function switch is not in operation, a trip signal shall be initiated
 - 3.2.2 Period: If the period becomes less than a preset limit, a trip signal shall be initiated
- 4.0 Power Source: The power source shall be 117 V $\pm 10\%$ ac; 60 Hz $\pm 10\%$. This power source shall supply all the needs of the chassis including trip circuits.
- 5.0 Size: The instrument shall not exceed 7 in. in height and shall be mountable in a standard 19-in. relay rack. The chassis shall be mounted in a drawer for easy removal.

D. Intermediate Range Monitor (Mean Square Voltage)

- 1.0 Log N Level
 - 1.1 Range: 0.00155 to 6.0 V true root mean square
 - 1.2 Meter Scale: Power-Percent 10^{-5} to 150 logarithmic in 7.176 decades
 - 1.3 Adjustability: Any root-mean-square voltage between 3.0 and 6.0 V shall be adjustable to read 150% power
 - 1.4 Accuracy: The observed log level shall not deviate from the true log level by more than $\pm 2\%$ of equivalent linear full-scale recorder output over the top six decades and not more than $\pm 5\%$ over the bottom decade under the combined variations of temperature, humidity, and line voltage
 - 1.5 Drift: Drift shall be less than $\pm 1\%$ of full scale in 100 hr under the combined variations of temperature, humidity, and line voltage
 - 1.6 Log N Level Response Time: The time constant (0-63%) of the log N to a positive-step-input voltage with no greater than 25% change shall be within the limits shown in the following table:

	<u>Voltage, V</u>	<u>Time Constant, sec</u>
	0.0015-0.006	20
	0.006-0.019	2
	0.019-0.060	0.2
	0.060-6.0	0.02 or better
- 1.7 Calibration: A built-in calibrator shall provide three calibration signals at 150, 10, and $10^{-3}\%$ power
 - 1.8 Outputs
 - 1.8.1 Recorder Output: 0 to 10 mV dc
 - 1.8.2 Meter Output: G.E. DB-40, taut band, 1%, 7.1-in. scale or equivalent, chassis-mounted. A 0-1 mA full-scale signal shall also be available for driving a remote meter.
 - 2.0 Period Meter: Same as for Source Range Monitor, except:
 - 2.5 Period-meter Response: The period meter shall not respond to signals less than 0.01 V root mean square
 - 3.0 Trip Circuits: Same as for Source Range Monitor
 - 4.0 Power Source: Same as for Source Range Monitor
 - 5.0 Size: Same as for Source Range Monitor

E. Power Range Monitor

- 1.0 Current Amplifier
 - 1.1 Range: 1×10^{-6} to 2×10^{-3} amperes input current for full-scale (125%) indication
 - 1.2 Meter Scale: 0 to 125% power
 - 1.3 Adjustability: Any input current between 2×10^{-4} and 2×10^{-3} amperes can be adjusted to read 125% power
 - 1.4 Accuracy: The observed current shall not deviate from the true current by more than $\pm 2\%$ of full scale under the combined variation of temperature, humidity, and line voltage
 - 1.5 Drift: Drift shall be not more than $\pm 1\%$ of full scale in 100 hr under the combined variation of temperature, humidity, and line voltage
 - 1.6 Current Amplifier Response Time: The time constant (0-63%) of the power range monitor to a positive step-input current shall always be less than 1 msec
 - 1.7 Input Polarity: Positive (current flows into amplifier)
 - 1.8 Calibration: Adjustable calibration test signals shall be built in to check three power levels

1.9 Outputs

1.9.1 Recorder Output: 0 to 10 mV dc

1.9.2 Meter Output: G.E. DB-40, taut band, 1%, 7.1-in. scale or equivalent, chassis-mounted. A 0-1 mA full-scale signal shall also be available for driving a remote meter.

2.0 Trip Circuits: Same as Source Range Monitor except:

2.1 Trip Functions: Four shall be provided

2.1.1 Chassis Interlock: If the chassis is removed from the drawer or the function switch is not on OPERATE, a trip signal shall be initiated

2.1.2 High Level No. 1: If the power level exceeds a preset level, a trip shall be initiated

2.1.3 High Level No. 2: Same as 2.1.2

2.1.4 High Level No. 3: Same as 2.1.2

3.0 Power Source: Same as Source Range Monitor

4.0 Size: Same as Source Range Monitor

F. Polarizing Voltage Power Supply

A high-voltage power supply for detector excitation shall be provided.

1.0 Range: -500 to -800 V dc

2.0 Adjustability: Six 50-V steps

3.0 Regulation: Less than 1% of voltage for 3-mA load

4.0 Ripple: Not observable as noise in the Source or Intermediate Range Monitor

5.0 Isolation from Common Ground: The high-voltage output shall be isolated from common ground and shall not produce a leakage current of more than 1×10^{-6} amperes as indicated on the Power Range Monitor

6.0 Trip Circuits: Same as Source Range Monitor except:

6.1 Trip Functions: Two shall be provided

6.1.1 Chassis Interlock: If chassis is removed from the drawer, a trip signal shall be initiated

6.1.2 High-voltage Monitor: The polarizing voltage shall be monitored at the detector or after all filter elements, and a trip shall be initiated if the voltage falls below a preset limit

7.0 Power Source: Same as Source Range Monitor

8.0 Size: Same as Source Range Monitor. (This supply can be included as a part of each instrument with only one being used.)

III. Packaging

1.0 Instruments: The basic circuit package shall be a glass epoxy board on which circuits and components are mounted. The circuit board shall be mounted in a totally enclosed housing, which protects it from damage. An easily removable cover shall provide access for servicing. Test points and adjustments shall be brought out the top of the module so that they are accessible without removing the module from service. Each module shall have an attached handle to facilitate removal. The modules shall be held in place by a card file that guides the connector into alignment with the mate.

The connector shall utilize crimp or connections that can be removed for servicing and repair. All low-level signal leads shall be coaxial and brought through the connector on coaxial connectors to minimize noise pickup, impedance matching, and leakage resistance problems.

The modules shall plug into a card file mounted in a drawer. The drawer shall be mounted on roller-bearing slides. In the fully closed position, the drawer shall lock into the relay rack by means of two knurled-knob latches with positive action. The drawer may be withdrawn on the slides to a limit stop, which shall allow access to all test points and adjustments. These limit stops may be released and the drawer removed completely. The cable connections to the drawer shall be mounted on the top rear surface of the deck in plain view. A drawer may be removed from the panel and replaced from the front without need for rear access to the relay rack. The connectors shall be keyed so that they cannot be misconnected. A common identifying nomenclature shall be used for the connectors on all monitor drawers.

Test points shall be provided on each module as needed for use in routine troubleshooting. For more thorough troubleshooting, a module extender shall be supplied. In this mode of operation, the entire circuit can be operated such that full access to all circuit points under energized conditions shall be realized.

2.0 Remote Amplifier: The remote amplifier shall be constructed so that it can be located as near to the reactor as possible while staying outside the biological shield, the purpose of which is to minimize the distance between the remote amplifier and the detector. The remote amplifier shall receive power from the Intermediate Range Monitor. The detector polarizing supply shall not be routed through the remote amplifier but directly to the detector. The remote amplifier shall be packaged in a manner consistent with a minimally susceptible subsystem. A shielded, gasketed, and decoupled enclosure shall be provided. Filtering and shielding of the input power leads to the remote amplifier shall be done to minimize line-conducted interference. The signal cables shall also provide adequate shielding.

3.0 System: The Source, Intermediate, and Power Range Instruments, as well as the Polarizing Power Supply, shall be mounted in a suitable portable enclosure. The enclosure shall be made large enough to accommodate at a later time a strip-chart recorder similar to a Brown Instrument Model 16 and safety and alarm logic circuits. The system shall be supplied completely interconnected. Only a 117-V 60-Hz ac supply shall be required. Only three cables shall leave the enclosure for the remote amplifier and detector, namely the polarizing voltage, remote-amplifier power, and signal cables.

4.0 Cables: 400 ft of suitable interconnecting signal and remote amplifier cable, 480 ft of suitable interconnecting polarizing voltage cable, and 80 ft of suitable interconnecting cable between the detector and remote amplifier shall be supplied, all complete with connectors attached.

IV. System Tests

The vendor shall conduct suitable tests on the complete package to verify acceptable system performance prior to shipment. The buyer shall have the option of witnessing a separate system-performance test prior to shipment. The vendor shall further guarantee a field operative system and provide competent field engineering to correct system defects and noise interference.

V. Instruction, Operating, and Maintenance Manuals

Three copies of a manual describing the operation, design, and troubleshooting of each instrument chassis, as well as the remote amplifier, shall be supplied. These copies of a document describing the complete system, as well as the interconnection drawing, shall also be supplied.

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