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ABSTRACT

This system uses a large organic scintillator as a moderator for a burst of fast neutrons, many of which are subsequently captured by the hydrogen in the scintillator. The pulses produced by the 2.2-Mev capture γ-rays are observed by four photomultiplier tubes whose anodes are paralleled. The output pulses are amplified and counted by a 10 Mc scaler. The scaler is gated to count for 300 μsec after the pulse, during which interval background is very small. Statistically significant information on total neutron output may be obtained for as few as 10^3 neutrons per pulse, with practically no upper limit. Relative calibration of the system is simple, and absolute calibrations are stable and reproducible.

AN EFFICIENT COUNTING SYSTEM FOR THE DETECTION OF NEUTRONS FROM LOW-YIELD PULSED NEUTRON SOURCES*

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INTRODUCTION

An efficient detector for the determination of yield of a low-yield pulsed neutron source should have the following characteristics: For unambiguous interpretation in digital form, the detector should respond to individual events. One must be able to check the relative sensitivity of the detector with respect to some known reference. Finally, a means must exist for obtaining an absolute calibration of the detector.

Such a neutron detector could be designed to record the prompt reaction events produced by fast neutrons, e.g. proton-recoil counters and fission counters. In the case of a pulsed source of neutrons, however, difficulty is encountered in that all the events are bunched together during the burst and a microsecond or so after it. With even moderate yields the events pile up with attendant counting difficulties. If however, the neutrons are slowed down, several advantages accrue:

(a) If the detection is by activation, reaction cross sections are often much higher for capture of thermalized neutrons.

(b) If the detection is accomplished by counting the prompt reaction products resulting from capture, advantage may be taken of the relatively long lifetimes of thermalized neutrons in a moderator, in order to spread the events out in time.

(c) Counting during the period of the neutron burst, with attendant X-rays and electrical noise, is obviated.

In commonly employed moderated systems, detection is accomplished by:

(a) Irradiating indium or silver and counting the induced activity after the burst.

(b) Counting scintillations resulting from capture of thermal neutrons in a lithium iodide (Tl) crystal.

(c) Proportional counting of alpha particles from thermal-neutron capture in BF_3 gas.

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(d) Counting the products of neutron capture in an organic scintillator, perhaps especially prepared to contain an ingredient with a high cross section for capture.

In all of these systems, the counting rate decreases markedly during the counting interval, with an exponential time dependence. For example, in the case of silver, the observed decay is almost solely from Ag^{110} (τ = 35 sec), and in the case of capture products, the observed decay is characteristic of the capturing medium and the geometry (typically τ = 1 to 200 μsec). In order to preserve the linearity of counts with yield, there is an upper limit to the total number of counts that can be accepted, and this limit is proportional to $1/T_r$ where T_r is the resolution time of the system for periodic pulses. Values of T_r for several detection systems are tabulated below:

Detector	T_r (μsec)	Limiting factor
Silver activation	2×10^2	Dead time of Geiger-Mueller tube
LiI or BF_3	2 to 5	Characteristic pulse shape and perhaps scaler
Organic scintillator	0.1	Scaler

The lower limit is imposed by the background count on each system.

Since the decay is a random phenomenon, in order to insure that two events do not occur within the resolution time of the system, it is reasonable to require that the initial counting rate $\dot{N}_{actual}$ is (1/10) $(1/T_r)$. This implies $\dot{N}_{observed}/\dot{N}_{actual} = 1/(1+T_r\dot{N}_{actual}) = 0.91$, and the observed number of counts $N_{observed}$, obtained by integrating the above expression, is approximately $(1-0.5\ T_r\ \dot{N}_{initial})\ N_{actual} = 0.95\ N_{actual}$.

If background is taken into account, the total number of counts in an interval $t_2 - t_1$ is, when coincidence loss can be neglected,

$$N = \tau(\dot{N}_{t_1} - \dot{N}_{t_2}) + \dot{N}_B\ (t_2 - t_1) \qquad (1)$$

where τ is the mean life and $\dot{N}_B$ is the background counting rate. In case of a detector of prompt reaction products, the second term can be made essentially zero if the counting period is restricted to a small interval after the burst. If, furthermore, the interval encompasses several mean lives, the expression reduces to $N = \tau\dot{N}_{t_2} = \tau/(10\ T_r)$.

In case of a silver activation, the background counting rate is such that the observed number of counts loses statistical significance at low neutron yields, so that its usefulness is limited to sources above about 10^6 neutrons per burst.

The mean life of thermal neutrons in a moderator can be estimated by solving the time-dependent diffusion equation

$$\frac{\lambda}{3}\nabla^2\phi - \Sigma\phi - (\partial\phi/\partial t)/v = 0 \tag{2}$$

where ϕ is the neutron flux and Σ is the macroscopic cross section for capture. We assume that an equilibrium distribution in the fundamental mode exists at the beginning of the counting interval. This yields

$$\tau = [(\lambda v B^2)/3 + \Sigma v]^{-1}, \tag{3}$$

where B^2, the buckling, is strictly a function of the geometry of the moderator such that B^2 goes to zero in the case of an infinite medium (corresponding to τ_∞). The value of λ, the transport mean free path, is computed from the value for water by assuming that, in each case, it is inversely proportional to the concentration of hydrogen atoms in the moderator in question. The mean life, τ, has been computed for a cylinder 7 in. in diameter and 10 in. high. In Table I, Eq. (3) has been evaluated for various moderators.

If we assume a representative value for τ of 140 μsec, the maximum number of counts, $N = \tau/10T_r$, computed for the various detectors is:

Detector	N
Geiger-Mueller tube	0.07
LiI or BF_3	2.8 to 7.0
Organic scintillator*	140

*No B or Cd additives

It appears that only with the organic scintillator can a statistically significant number of counts be obtained. Although it is advantageous to make the moderator large to maximize τ and therefore N, a more overriding consideration is the efficiency as a function of size. The quanitity τ/τ_∞ is the absorption efficiency for thermalized neutrons, which, from the table, is about 0.4 for an organic scintillator of the dimensions referred to above.

It is possible to improve the efficiency for thermal-neutron capture by dissolving compounds of boron or cadmium in the scintillator. In the case of cadmium, a significant increase in pulse height is achieved in addition. However, this higher efficiency (of the order of 2) is obtained at the expense of drastically shortening (of the order of 50) the lifetime of the neutrons in the scintillator, with corresponding decrease in the number of counts that can be accepted without serious coincidence loss. Thus, the addition of these substances is not desirable for this application.

Table I

Value of mean life of thermal neutrons in various moderators

Moderator	Formula	Density, ρ (gm/cc)	H atoms/cc	λ (cm)	τ_∞ (μsec)	τ (μsec)
Water	H_2O	1.00	6.7×10^{22}	0.43	226	139
Paraffin	$C_{25}H_{52}$	0.89	7.9×10^{22}	0.36	192	132
Polystyrene	$C_6H_5CHCH_2$	0.91	4.2×10^{22}	0.69	361	141
Toluene	$C_6H_5CH_3$	0.87	4.5×10^{22}	0.64	336	141

CONSTRUCTION OF THE ORGANIC SCINTILLATION DETECTOR

Several scintillation counters have been constructed for the efficient detection of neutrons from low-yield pulsed sources by the capture of neutrons in the hydrogen of the scintillator. Both solid (p-terphenyl in polystyrene) and liquid (p-terphenyl in toluene) types have been used successfully.[1] The solid form is preferable from the standpoint of ease of handling and because it has no tendency to become contaminated by dissolving sealing materials, etc., as does the liquid. However, the difficulty of obtaining large castings has limited the solid plastics to dimensions not much larger than those previously referred to. A typical solid scintillator assembly is shown in Fig. 1. With this construction, conversion to a liquid scintillator may be made with only minor modifications. In the assembly, the plastic is tightly encased in aluminum foil for good light reflection, with the sides and bottom of the plastic crazed to prevent multiple external light reflections. The polished end of the scintillator is viewed by four RCA type 6655A 2-in. photomultiplier tubes. The RCA 6655A is flat-faced, free from afterpulsing, and has a uniform sensitivity and pulse transit time across the photocathode face, which factors governed its choice for this application. Optical contact is made with Dow-Corning No. 200 silicone fluid, which has a viscosity of 65,000 centistokes or higher. In the case of a liquid counter, the tubes are immersed to a depth of about 1/2 in. A 1/8-in. lead X-ray shield surrounds the plastic. All of this is inside a light-tight aluminum tank with a bolt-down top provided with metal pipes through which the photomultiplier tubes are inserted and taped in place in contact with the scintillator. The tube sockets, wiring, and external electrical connectors are contained in a sheet metal cover which fastens to the tank top.

ELECTRONICS

High voltage for the photomultipliers is supplied by a precision regulated (negative-polarity) power supply. Four potentiometers allow individual voltage settings to be made on each tube. The anode connections are paralleled, and the signals (negative pulses) are brought on a 185-ohm RG 114/U cable to two Hewlett-Packard 100-Mc band-width pulse amplifiers, a 460A and a 460B. The latter inverts the pulse, The amplifiers are followed by a Hewlett-Packard Model 520A scaler with a resolution time of 0.1 μsec. The scaler has been modified to provide a pulse-height discriminator and to allow it to be gated. Since this scaler has a scale factor of only 100, it is followed by a conventional (T_r = 2 to 5 μsec) scaler. The fast scaler is gated by a gate (+ 20 v) generator which is continuously variable from 0 to 1 sec in both gate delay and gate width. A block diagram of these components is shown in Fig. 2.

SELECTING THE GATE

Two criteria determine the optimum gate delay. It is necessary to delay the gate until the amplifiers have recovered from the prompt proton-recoil pulse resulting from the slowing down of the fast-neutron burst in the scintillator. Also, it is necessary to wait until the initial counting rate is reduced to 1/10 T_r to avoid excessive coincidence-counting loss. A check on the first condition may be made by observing the amplifier output on an

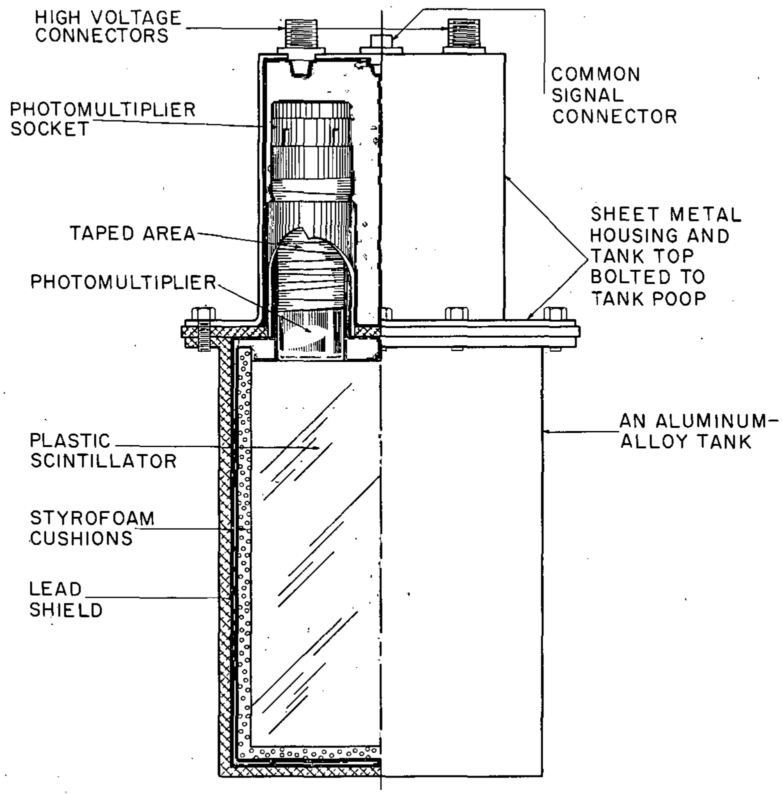

Fig. 1. Scintillator construction.

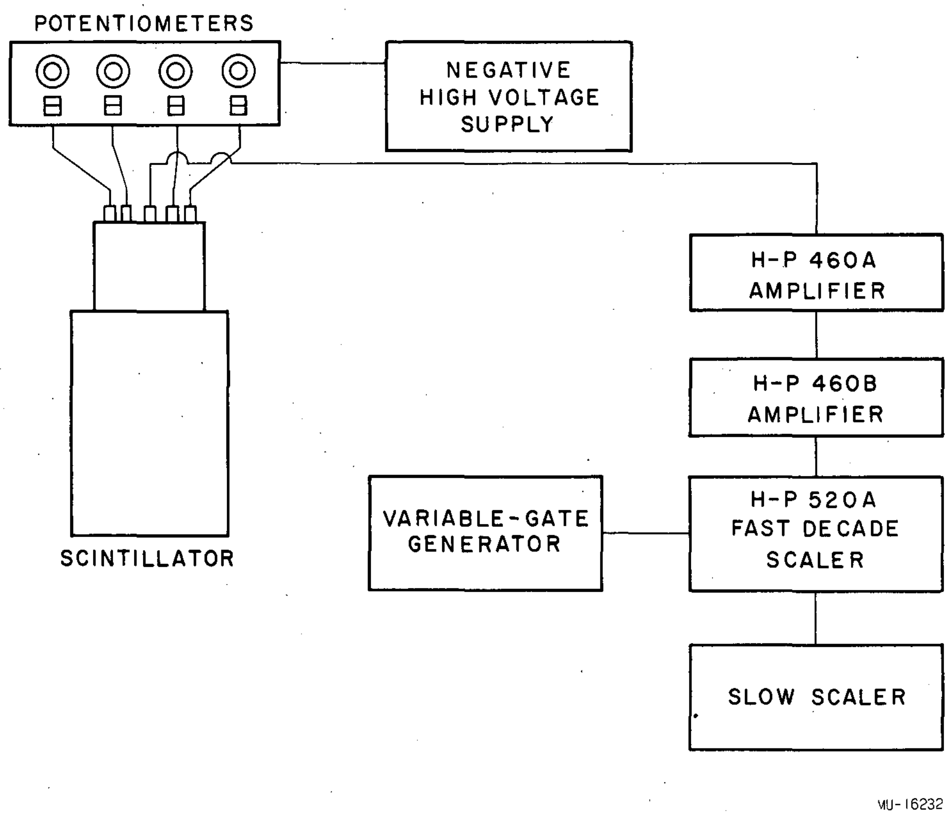

Fig. 2. Block diagram of electronics.

oscilloscope and noting when the amplifier base line returns to normal after a burst. A check on the second may be made by successively delaying the gate and recording counts, firing the same number of bursts for each position, with constant neutron output in each burst. When plotted on semi-log paper with observed counts versus gate delay, the data should fall on a straight line (from whose slope the half life for thermal-neutron capture in the scintillator may be determined.) Any tendency of the high count-rate data to fall below this line is an indication of coincidence loss. An example of such a plot is given in Fig. 3. It is unwise to gate both the fast and slow scalers, for if the count rate should be high at the end of the gated interval, the fast scaler may produce an output pulse after the end of the gated interval due to inherent delays in its read-out circuits, and this would not be counted by the slow scaler.

The gate width is selected from considerations of obtaining essentially all of the available information without including an objectionable background count during the gate interval. We have standardized on a gate width of 300 μsec, which is approximately 3 half lives and includes 7/8 of the total counts. Background contribution under these conditions is very low (i. e., 0.05 counts per gate).

RELATIVE CALIBRATION

It has been found quite practical to use a gamma ray from a radioisotope to obtain a check on the relative over-all gain of the system and also to set the individual gains of the photomultiplier tubes. Cs^{137} decays by beta emission to Ba^{137} which then emits a monoenergetic 662-kev gamma ray. The interaction of this gamma ray in the scintillator is almost entirely by Compton scattering. The distribution of pulse heights observed from the scintillator has a fairly well-defined upper limit which corresponds to total absorption of the energy of this gamma ray. The sharpness of this upper limit is influenced by three factors:

(a) The optical quality of the scintillator. If the scintillator attenuates its own light output appreciably, an event distant from the photomultiplier tubes will give a lower pulse than an identical event nearer to them.

(b) The intensity of the source. If the source is too weak, its pulses cannot be discerned against the wide spectrum of background pulses. A source strength of about 10^7 disintegrations per minute has been found satisfactory.

(c) The match of the gain of the photomultiplier tubes. If they are quite different, a spectrum of pulses will result from identical events depending upon where they occur with respect to the various tubes.

The photomultiplier tubes are matched in gain by setting the individual high-voltage potentiometer for each tube until it produces the maximum pulse of 1.0v from Cs^{137}, viewed after the amplifiers. The combined output is then adjusted with the main high-voltage control until the maximum appears at 5 v, where it enters the fast scaler, whose discriminator has been set to accept pulses of 2.5 v and higher. This places the system

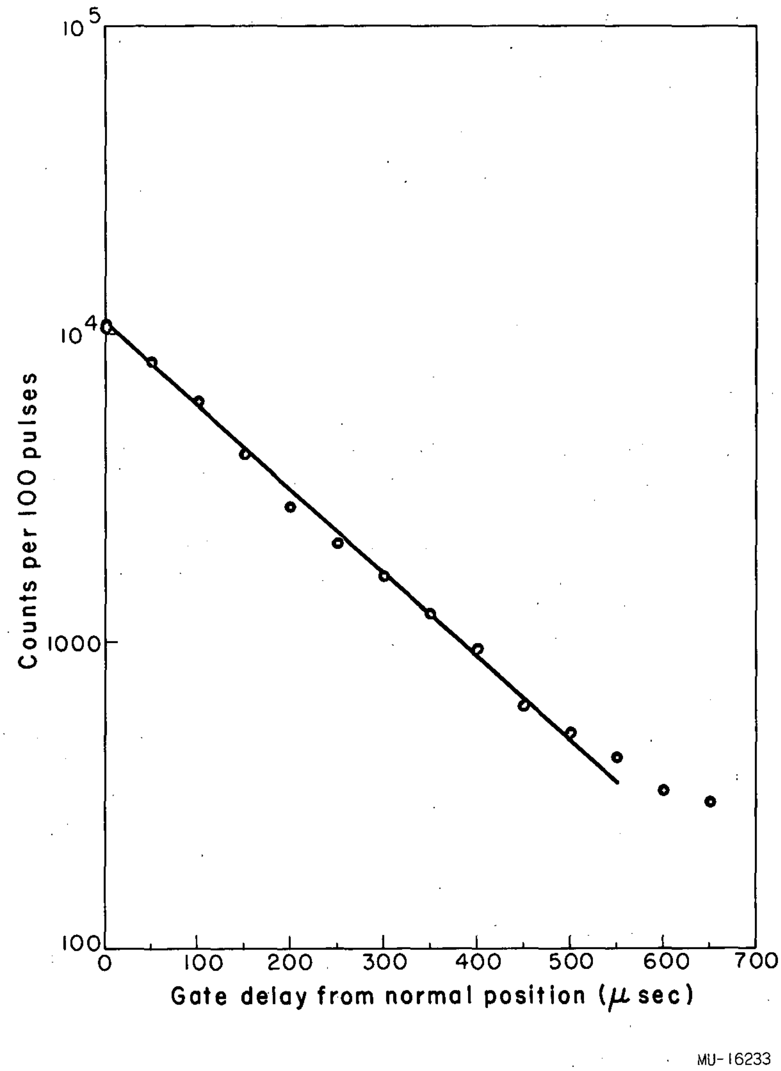

Fig. 3. Counts recorded vs scalar gate delay. Slope corresponds to 112 μsec half life. Room neutrons affect linearity after 550 μsec.

near the low-voltage end of the observed neutron-capture pulse plateau (Fig. 4) and does not introduce more background counts than necessary. The Cs^{137} source must be removed to a suitably shielded location during neutron counting to prevent its contributing to background.

In order to accentuate the pulse-height cutoff as observed on the oscilloscope, it is desirable to employ a cathode-ray tube (CRT) which does not have a persistent screen, and to reduce the CRT intensity until single traces are not seen.

ABSOLUTE CALIBRATION

Absolute calibration of this detector system may be accomplished by the following means:

(a) Directly, by exposure to known-intensity bursts of neutrons from a Van de Graaff or Cockcroft-Walton accelerator and using either the $D(d,n)He^3$ or the $D(t,n)He^4$ reaction. The absolute neutron flux is determined by counting charged particles from the reactions, and solid-angle measurements must be carefully made. The resulting calibrations for D-D (2.5-Mev neutrons) and for D-T (14-Mev neutrons) will differ because of the decreasing ability of the scintillator block to thermalize the neutrons as the incident neutron energy increases.

(b) Indirectly, by comparing counts obtained on the scintillator system with those from an activation detector that has been previously calibrated as outlined in (a) above. In the case of silver activated by thermal neutrons, counting of the 24-sec beta activity requires about one minute after the burst. A "cooling off" period for the silver of 4 minutes between bursts is necessary. Since the background of the beta counter is appreciable, the yield from a pulsed neutron source must exceed about 10^6 neutrons per pulse for a measurement with reasonable statistical significance. Again, the sensitivity of the activation detector varies with neutron energy, so both primary calibration and use with the pulsed neutron source must involve the same neutron energy.

(c) Indirectly and less accurately, by comparing, with both counters suitably gated, the scintillator counts per burst with counts obtained on a BF_3 "long" counter which has been calibrated against a known-intensity radioactive neutron source, such as Ra-Be, at the same location as the pulsed neutron source. The scintillator cannot be calibrated directly with a radioactive neutron source because gamma rays from the source as well as the neutron counts are recorded; in an uncertain ratio. With this method, the BF_3 counts obtained from the pulsed source must be corrected for count loss during the gate delay time. If the gate delay of the BF_3 is t_1, the factor $e^{t_1/\tau}$ will correct the BF_3 observed counts, where τ is the mean lifetime of neutrons in the BF_3 moderator. The scintillator efficiency is then given by

$$\epsilon_{sc} = \epsilon_{BF_3} N_{sc}/(N_{BF_3} e^{t_1/\tau}) . \qquad (4)$$

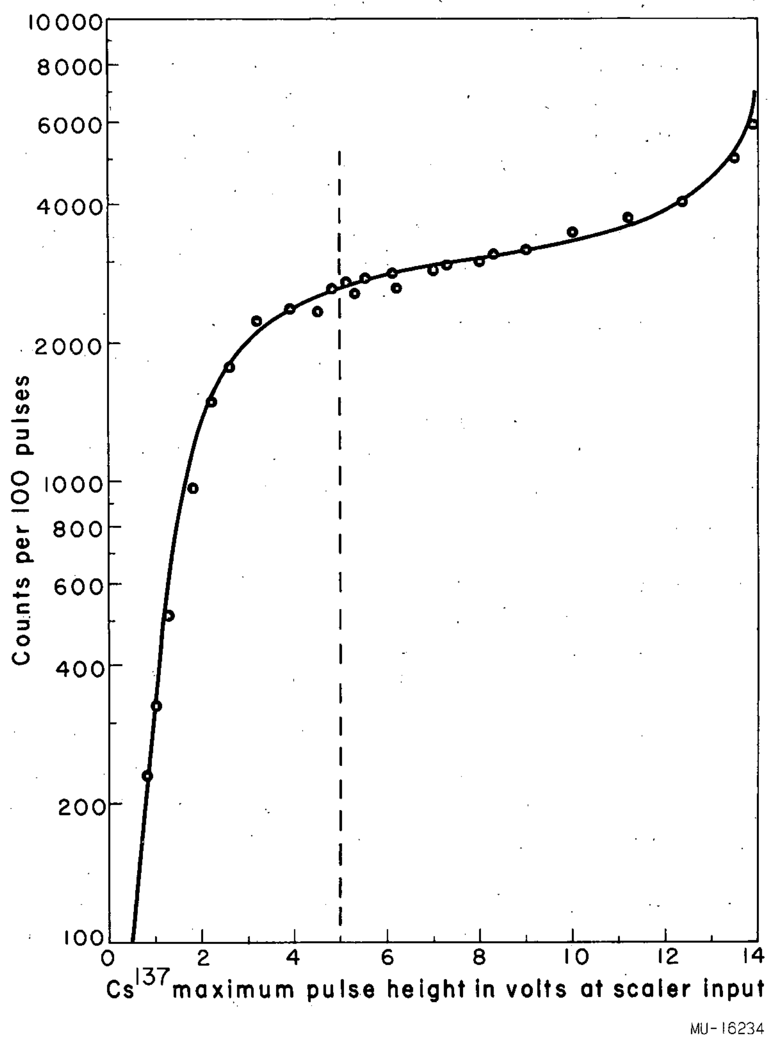

Fig. 4. Neutron-capture pulses in plastic scintillator 7 in. diam. and 10 in. high. Scaler discriminator is set at 2.5 volts. Recommended gain setting for abscissa is 5.0 volts.

This method neglects the correction for the differing sensitivity of the BF_3 counter to neutrons from the pulsed source and from the radioactive source.

In general use with pulsed neutron sources of wide variability in neutron output, it will be found that the maximum allowable number of counts acceptable will be exceeded for high burst intensities. The counts may be brought into the desired range by calibrating the counter for several detector-to-target distances, or by delaying the scintillator scaler gate by an amount sufficient to reduce the counts to the level desired. As described previously, if recorded counts are plotted against gate delay, the half life of the neutrons in the scintillator may be determined. If the gate is delayed a time, t, the count obtained, using the same gate length, will be down by a factor of $e^{-t/\tau}$ from that which would be present in the normal gate-delay position. It can be seen that if the gate is delayed one half life from normal position, the counts will be reduced to one-half. Once the half life has been accurately determined, this method becomes a convenient and flexible means of controlling the number of counts accepted without changing the calibration values previously obtained.

Once obtained, the calibrations should be quite stable. As the system is set to operate on a neutron-capture pulse plateau, small changes in the over-all gain of the system due to drifts of high voltage, amplifiers, scaler sensitivity, etc. have little effect on the detection efficiency.

However, efficiency, and hence calibration is sensitive to accurate measurement of source-to-detector distance, and orientation, and also to the presence of significant amounts of neutron-moderating materials in proximity to either the neutron source or the detector. These materials should be kept to a minimum. The effect of room-reverberation neutrons, which can contribute a half life in the 1 to 2 msec range, can be reduced by surrounding the scintillator with boron or lithium shielding material.

EFFICIENCY

The theoretical efficiency of this counter has been calculated by Monte Carlo methods with the aid of an IBM-704 computer. The results are summarized in Table II below for a plastic block 7-in. diam. by 10-in. long (polystyrene).

Table II

Theoretical efficiency of counter for 14-Mev and 2.5-Mev neutrons		
Calculated item	14 Mev	2.5 Mev
Total emission in 4 π solid angle	32,895	32,895
Total sample used, contained in solid angle	2,500	2,500
No. in sample that miss block	830	830
No. in sample that hit block	1,670	1,670
Percentage of total that hit block	5.05	5.05
Mean free path for first collision, in cm	14.3	4.07
Total leaking from block or fast-captured in C or H	1,559	1,411
Total arriving with energy of 0.04 ev	111	259
No. with energy of 0.04 ev that remain after 10 μsec	0	0
Percentage of those hitting block that arrive at 0.04 ev	6.66	15.5
Percentage of total emission that arrive at 0.04 ev	0.337	0.790

These results are for a distance of 8 in. measured from the side of the scintillator block to the source, with the source centered with respect to the side of the block. The effects of elastic and inelastic scattering from carbon have been included. The efficiency figures given are to be corrected further to take into account those neutrons that leak from the block without being captured after reaching thermal energies, a previously determined factor of τ/τ_{∞} = 141/361 = 0.39. Applying this to the efficiency figures above, we have:

	14 Mev	2.5 Mev
Intrinsic efficiency (%)	2.60	6.10
Efficiency at 8 in. (%)	0.132	0.308

Experimentally determined efficiencies are lower than these, because of absorption of neutrons in the scintillator tank and shielding, and because the neutron-capture pulse plateau is not really flat, i.e., there is a spectrum of pulse heights, and the smallest pulses fall beneath the discrimination level of the fast scaler. Average values of experimentally determined efficiencies for three such counters under these conditions are:

Neutron energy in Mev	Measured efficiency at 8 in.(%)
14	0.120
2.5	0.271

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1. Gow, Ruby, Smith, and Wilcox, The Trapping of Charged Particles in Axially Symmetrical Systems of Electric and Magnetic Fields, UCRL-8156, January 24, 1958.

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