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Potential and Limitations of Several Neutron Coincidence Equipments

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49

CONTENTS

ABSTRACT

Coincident neutron detectors which can distinguish between neutrons occurring as a result of fission and those due to (α,n) or (γ,n) nuclear reactions have been described (NRL Memorandum Report 2107). In this report, several methods of developing follow-on equipments with greater potential for the nondestructive assay of plutonium samples are examined. The effect on equipment performance of the efficiency and neutron lifetime in the neutron detector and of analysis gate length and equipment dead times are treated in considerable detail and several illustrative examples are presented. Performance is generally improved by an increase of neutron efficiency accompanied by a decrease in neutron lifetime and the use of optimized analysis circuitry. Good performance can be obtained with rather complex 4π moderating detectors which employ an array of enriched BF_3 or ^3He neutron detection tubes dispersed in a hydrogeneous moderator. The use of a large liquid scintillation detector may be an ideal approach if adequate discrimination against interfering pulses can be obtained.

PROBLEM STATUS

This is an interim report on the problems; work is continuing.

AUTHORIZATION

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POTENTIAL AND LIMITATIONS OF SEVERAL NEUTRON COINCIDENCE EQUIPMENTS

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INTRODUCTION

An attempt is made to examine the effect of detector and analysis circuit parameters upon the potential and limitations of certain neutron coincidence techniques as applied to the nondestructive assay of plutonium samples. The purpose is to ellucidate in a general fashion the parameters necessary to obtain a given performance. The objective is to furnish a basis for choosing the more promising approach or approaches toward achieving more powerful future equipments.

The fissometer approach which involves a single moderating detector and the recognition of coincidence neutrons by an analysis of the neutron pulse spacing is treated in considerable detail.[1] Brief consideration is given to the Rossi alpha method of analyzing the output of a moderating detector and to the use of proton recoil detectors.

FISSOMETER PERFORMANCE RELATIONS

In the fissometer, a single moderating detector is employed and the data recorded is the total number of neutron pulses observed (designated as E), the number of pulses observed during a series of time periods of length τ starting shortly after the arrival of each pulse which initiates an analysis cycle (designated as R) and the number of pulses observed during a series of time periods of length

T which are delayed relative to the start of the analysis cycle by a time large compared to the neutron lifetime in the detector (designated as A). A measure of the coincidence neutrons resulting from fissions is obtained from the difference of R and A (designated by N = R - A).[1]

Samples specifically considered consist of Pu-240 which undergoes spontaneous fissions. In addition, nonfission neutron produced counts are included which, for a detector sensitive only to neutrons would result from (α,n) reactions in the sample and possibly from (γ,n) reactions in the detector. The inclusion of nonfission pulses in the analysis permits the consideration of γ-ray produced pulses in an actual detector.

The equipment characteristics which dictate the measurement potential include the neutron detection efficiency (ϵ), the differential neutron lifetime in the detector (ℓ),[2] analysis circuit gate length (τ), the various equipment dead times and any equipment idiosyncracies such as an imbalance between the number of openings or the lengths of the R and A gates.

Considering a pure fission source, the total number of pulses, E_f, is related to the number of fissions, F, by

$$E_f = F \bar{\nu} \epsilon \qquad (1)$$

in which $\bar{\nu}$ is the average number of neutrons emitted per fission and ϵ is the neutron detection efficiency in counts per source neutron, In the analysis, $\bar{\nu}$ is assumed to be the average number of prompt neutrons; the error involved is unimportant for the purposes at hand.

The ideal gross count rate, E_t, (the rate which would be observed in the absences of dead time losses) is taken as

$$E_t = C \ (1 + \alpha) \ m \ \epsilon \tag{2}$$

in which m is the mass of Pu-240, and α is the ratio of counts <u>not</u> due to fission neutrons to counts due to fission neutrons. C is the product of the Pu-240 spontaneous fissions per gram per unit time and the average number of neutrons per fission; C is taken as 10^3 sec^{-1}.

Some fraction of the fission events will cause two or more pulses in the detector. In analyzing fissometer performance, a quantity of prime interest is the fraction of the fission-produced pulses which may be designated as subsequent or following pulses; these include the second pulse of a pair of pulses from a single fission, the second and third of three pulses from a single fission etc. In Appendix A, Table A2, the ratio of following pulses, E_s, to the total number of prompt fission neutron produced pulses, E_f, is given based upon constants believed applicable to Pu-240. This ratio is a strong function of ϵ. A ratio which varies more slowly with efficiency is $E_s/\epsilon\, E_f$ which is also tabulated in Table A2; this ratio varies from 0.90 to 0.68 as ϵ varies from 0 to unity.

The ideal net count rate is taken as

$$N_\ell = F_s\, e^{-t_o/\lambda} \left(1 - e^{-\tau/\lambda}\right) \qquad (3)$$

in which F_s is the following counts per unit time for the source involved, t_o is the time interval between the arrival of the pulse which initiates the analysis cycle and the opening of the R gate, τ is the gate length and λ is the differential neutron lifetime in the detector. For convenience a quantity R_s is defined as

$$R_s = \frac{1}{\left(\dfrac{F_s}{\epsilon\, F_f}\right) e^{-t_o/\lambda} \left(1 - e^{-\tau/\lambda}\right)} \qquad (4)$$

For equipment with $t_o \ll \lambda$ and $\tau = 1.1\,\lambda$, values of R_s given in Table A2 range from 1.67 to 2.59 as ϵ ranges from zero to unity. Employing R_s, eq. (3) may be written as

$$N_\ell = \frac{C\, m\, \epsilon^2}{R_s} \quad . \qquad (5)$$

Dead time losses in the gross channel can cause the loss of coincidence information. Considering the situation in which an analysis cycle has been initiated by the first pulse of a multiple pulse event, one or more following pulses are expected along with pulses which are unrelated timewise to the initiating pulse. Three types of processes are of interest: first, unrelated pulses can "kill" other unrelated pulses; second, unrelated pulses can "kill" following pulses or vice-versa; and third, following pulses can "kill" other following pulses. The first type of process need not be considered since it will occur with equal probability during both the R and A gates and hence should on the average have no effect on the observed net count rate. The second type of process is of primary concern since it will reduce the observed net count rate; this process is dependent on the unrelated gross count rate. The third type of process will also reduce the net count rate, however, the reduction will be by a fixed percentage of the net count rate and will be independent of the unrelated count rate.

In the second type of process, a count will be lost (and hence an error will occur) if an unrelated count occurs within the dead time, t_1, either before or after the arrival of a following pulse. Presuming an exponential differential neutron lifetime, ℓ, the probability of a following count occurring per unit time is

$$P_s = \frac{n\, e^{-t/\ell}}{\ell} \tag{6}$$

in which n is the number of following counts associated with the count which initiated the analysis cycle and t is the time after the arrival of the initiating pulse. For count rates such that the probability of "double kills" (i.e. the loss of 2 counts during t_1) can be neglected, the probability of the loss of one count during the R gate is approximately

$$P_1 = \int_{t_o}^{t_o+T} \int_{t_s-t_1}^{t_s+t_1} n \frac{E_\ell \, e^{-t_s/\ell}}{\ell} \, dt_2 \, dt_s$$

$$= 2nt_1 \, E_\ell \, e^{-t_o/\ell} \, (1 - e^{-T/\ell}) \tag{7}$$

in which the subscript "s" applies to the following pulse and the subscript "2" to the unrelated pulse invovled. The expected fractional loss of net pulses which would be observed in the absence of dead time is obtained by dividing the above result by n, namely,

$$\text{fractional loss} = 2t_1 \, E_\ell \, e^{-t_o/\ell} \, (1 - e^{-T/\ell}). \tag{8}$$

The expected fractional loss of net pulses resulting from one following pulse and two unrelated pulses arriving during a dead time interval t_1 is approximately $3t_1 E_\ell/2$ times that given in eq. (8). It will be presumed that this type of loss can be ignored.

An examination of the third type of process is germane when reasonably efficient detectors are employed for which the probability of two or more following pulses per fission event should be taken into account. A first order analysis indicates that the fractional loss of net signal from this mechanism is

$$\frac{(n - 1)}{2} \frac{t_1}{\ell} e^{-2t_o/\ell} (1 - e^{-2T/\ell}) . \tag{9}$$

Thus for efficient detectors it is desirable to have $t_1/\ell \ll 1$ in order to minimize this type of loss.

One criterion necessary for good performance may be taken as

$$t_1 \ E_\ell < \beta(E_\ell, t_1) \tag{10}$$

in which β is a criterion constant to be chosen based upon the precision desired and a willingness to make appropriate corrections.

If, for illustrative purposes, $\beta(E_\ell, t_1)$ is chosen as 1% and using $C = 10^3$ then this requirement on t_1 is

$$t_1 \leq \frac{10}{\epsilon \ m(1 + \alpha)} \tag{11}$$

where t_1 is in μs.

The ratio of t_o to ℓ, which occurs in eq. (3), should be kept reasonably small, otherwise the net count is significantly reduced. Since the effective value of t_o is equal to or greater than t_1, an additional requirement on t_1 is implied.

For most circumstances, τ should be chosen to be roughly equal to or slightly larger than ℓ. While an optimum ratio applies to a given source and detector, the optimum value changes with source intensity and a compromise must be made appropriate for the range of source strengths of primary interest.

The ratio of accidental (A) to net (N) counts can be of considerable importance when actual equipments are considered. If A/N is large and any imbalance is present between the numbers or lengths of the R and A gates, significant errors in the deduced value of N will result. For ideal equipment this ratio is not important per se; the criterion then is the observation time required for a given statistical precision which is discussed below.

Eq. (A26) of Appendix A gives

$$\frac{A}{N} = \tau\ C(1 + \alpha)[R_s(1 + \alpha) - \epsilon]\ m. \tag{12}$$

The ϵ in the bracket can frequently be neglected giving the relation

$$\frac{A}{N} \approx C\ R_s\ \tau(1 + \alpha)^2\ m. \tag{13}$$

Equations for the observation time necessary to obtain a 1% statistical standard deviation, assuming ideal equipment operation, are developed in Appendix A. For the case where the analysis dead time is equal to the gate lengths

$$t(1\%) = \frac{10^4\ R_s}{C\ \epsilon^2\ m} + \frac{10^4\ \tau}{\epsilon^2}[2R_s(1 + \alpha) + \epsilon][R_s(1 + \alpha) - \epsilon]$$

$$+ \frac{2 \times 10^4\ \tau^2\ C(1 + \alpha)}{\epsilon}[R_s(1 + \quad) - \epsilon]^2\ m. \tag{14}$$

The case where $t_s \neq \tau$ is treated in eq. (A27).

SPECIFIC FISSOMETER EXAMPLES

The following examples are based either upon actual equipments (Case 1) or upon neutron detectors which have been employed in plutonium assay (Case 2) or in research (Case 3). In Cases 2 and 3 fissometer equipment roughly optimized to the differential neutron lifetime in the detectors is postulated.

Case 1, Brookhaven Built Equipment

Approximate parameters appropriate to the latest BNL equipment are efficiency (ϵ) = 0.1, gross dead time (t_1) = 8 μs, analysis gate length (τ) = 129 μs and analysis dead time (t_2) = 137 μs. The neutron lifetime in the counter with the two halves separated slightly has been measured by Weinstock as 82 μs.[3] Also, the period between the arrival of the initiating pulse and the opening of the R gate is ~ 8 μs. The convenient assumption will be made that the quantity $e^{-t_0/\ell}$ $(1 - e^{-\tau/\ell}) = 2/3$; no serious error is introduced by this assumption.

The gross channel dead time loss is calculated to be 1% when the quantity $m(1 + \alpha) = 12.5$ g and the corresponding gross count rate is 1,250 ct/sec or 75,000 ct/minute. At this count rate, the dead time loss is expected to reduce the net count rate by about 2%.

The ratio of A to N is calculated to be

$$\frac{A}{N} = 0.129(1 + \alpha)[1.746(1 + \alpha) - 0.1] \text{ m}$$

$$\frac{A}{N} \leq 0.225(1 + \alpha)^2 \text{ m}. \tag{15}$$

Since the R and A gates are believed to be very similar in both frequency of occurrence and in length, it will be presumed that no significant error in measured values of N is involved.

The observation time in minutes required to obtain a 1% statistical standard deviation is approximately

$$t(1\%,m) = \frac{29.10}{m} + 13.11(1 + \alpha)^2 + 0.180(1 + \alpha)^3\ m. \tag{16}$$

Case 2, Large LASL Detector

This detector has an efficiency of 0.37 and a mean neutron lifetime of about 33 μs.[4] For illustrative purposes, $\epsilon = 0.40$ and an analysis gate length and dead time of 40 μs is assumed. As above, $e^{-t_0/\ell}(1 - e^{-\tau/\ell})$ is taken to be 2/3.

For the gross channel dead time loss to be 1% or less requires that $t_1 \leq 25/m(1 + \alpha)$ μs.

The calculated A to N ratio is

$$\frac{A}{N} = 0.04(1 + \alpha)[2.00(1 + \alpha) - 0.40]\ m$$

$$\leq 0.080(1 + \alpha)^2\ m. \tag{17}$$

The calculated observation times in minutes corresponding to a 1% statistical standard deviation is approximately

$$t(1\%,m) = \frac{2.08}{m} + 0.3333(1 + \alpha)^2 + 0.00533(1 + \alpha)^3\ m. \tag{18}$$

Case 3, Diven et al. Detector

In the measurement of the distribution of the number of prompt fission neutrons, Diven et al.[5] employed a large liquid scintillation detector roughly 28 in. in diameter and 30 in. long. This scintillator was loaded with enough cadmium to reduce the mean neutron lifetime in the detector to about 15 μs.[6] Neutron capture events were identified by the large pulses produced by the deexcitation gamma rays associated with neutron capture in cadmium. For fission spectrum neutrons, an average efficiency of 83% was reported.

For illustrative purposes an efficiency of 0.8, a neutron lifetime of 15 μs and an analysis gate length and dead time of 20 μs will be assumed. To keep the gross channel dead time losses below 1% would require that $t_1 < 12/m(1 + \alpha)$ μs.

The calculated A to N ratio is

$$\frac{A}{N} = 0.02(1 + \alpha)[2.374(1 + \alpha) - 0.8]\ m$$

$$\leq 0.04748(1 + \alpha)^2\ m. \tag{19}$$

The calculated observation time in minutes corresponding to a 1% statistical standard deviation is approximately

$$t(1\%,m) = \frac{0.6182}{m} + 0.05870(1 + \alpha)^2 + 0.000939(1 + \alpha)^3\ m. \tag{20}$$

NONFISSOMETER TECHNIQUES

Rossi Alpha Approach

It has been suggested by Sastre of BNL[7] that coincidence measurements could be carried out using a technique similar to Rossi alpha measurements which have been used successfully in the determination of reactor parameters. A moderating detector would be employed and the analysis would consist of recording the number of pulses which arrived in each of a considerable number of equal time intervals following the arrival of any pulse which was able to initiate an analysis cycle. Pulses which are not related to an initiating pulse should be uniformly distributed in time and thus would on the average make equal contributions to all channels. The following pulses associated with initiating pulses, however, should lead to an exponential distribution which makes a maximum contribution in the first channel.

A measurement was carried out by Weinstock employing a 2 gram Pu-240 sample in one of the BNL fabricated detectors.[3] Because of the size of the sample, the two halves of the detector were separated by 1/4 to 3/8 in., thus increasing the neutron leakage from the detector relative to that of a closed detector. The analysis sweep was more than 512 μs long and the counts were stored in 256 time bins each of 2 μs width. During a 60 minute run 920,621 triggers (i.e. analysis sweeps) were recorded and the expected type of time distribution was observed. The uncorrelated component (approximated by the number of counts in the later time channels) was about 660 counts per 2 μs time bin. The count per 2 μs time bin extrapolated back to the zero channel was ~ 1780 of which ~ 1120 were due to correlated pulses. The difference between the observed count per bin and the uncorrelated count per bin followed an exponential function corresponding to a mean neutron lifetime in the detector of (83 ± ~ 3) μs.[8] The gross count rate, deduced from

$$A = G \tau E \qquad (21)$$

in which A is the average count rate at later times (count per bin - sec), τ is the 2 μs bin width, and G is the trigger rate (per second), is 360 counts per second. The coincidence component is consistent with the spontaneous fission rate expected in 2 gram of Pu-240. The deduced gross count rate implies that either a rather large number of (α,n) neutrons are produced in the sample or that gamma-ray pile up counts made an important contribution; the predicted gross rate for the spontaneous fissions alone is ~ 200 per second.

This measurement demonstrates that the Rossi alpha approach will yield the desired coincidence information. In addition, it conveniently yields a measurement of the neutron lifetime in the detector. Also, the shape of the time distribution gives added assurance of correct equipment operation. Its use in conjunction with gamma-ray measurements in which a pulse height analyzer is necessay for the gamma-ray data analysis might result in appreciable savings in overall equipment complexity. Provisions would need to be made for convenient analysis of the data such as the addition of the number of counts in an early group of channels to obtain a number corresponding to R of a fissometer and the addition of the number of counts in a later group of channels to give a number corresponding to the A of a fissometer.

The dead time limitations of this approach are expected to be more severe than for a fissometer. In the later Brookhaven built fissometers, separate R and A gates are provided and the analysis dead time is only slightly longer than a single gate width. If a single sweep circuit is to be employed (as was done by Weinstock) this sweep needs to be roughly the equivalent of two fissometer gate lengths if comparable coincidence information is to be obtained.

In addition to a gross dead time associated with the detector and amplifier (a dead time presumed comparable for both the fissometer and the Ross' alpha) an additional dead time in the latter is to be expected. After the arrival of a pulse during the analysis sweep, a period of time is required to route this pulse to its appropriate time bin. If another pulse arrives during this period, it may be lost. For the equipment used by Weinstock a 16 μs dead time of this type was present.[3]

The potential and limitations of the Rossi alpha approach are roughly the same as those of a fissometer provided the effects of the applicable dead times are taken into account. For this reason no further specific discussion of this approach is included.

Proton Recoil Detection

Several scintillators including stilbene and various plasti-scintillators can be used to detect fast neutrons using the scintillations caused by proton recoil events. Generally it is necessary to use pulse shape discrimination to reject the ubiquitous gamma-ray pulses if valid neutron measurements are to be made.

The fact that immediate pulses are obtained, rather than the delayed pulses of a moderating detector, suggests that some advantage might accrue for coincidence applications. A more careful analysis implies, however, that serious problems involving efficiency and dead time are present.

Since the proton recoil pulses from two coincident neutrons are essentially simultaneous, it appears that two detectors must be employed. If the occurrence of a fission is to be recognized by the occurrence of a pulse in each of two detectors, the probability of the fission being detected is about half that which applies to the fissometer case. Further, since it is usually necessary to apply a pulse height bias to the proton recoil pulses, not all of the neutron elastic scattering events will result in useful pulses. Thus the coincidence efficiency is expected to be significantly lower for two proton recoil detectors than for a single moderating detector.

Perhaps a more serious difficulty stems from a consideration of dead time associated with the gamma-ray pulse rejection. Characteristically a period of roughly a microsecond is employed to classify a pulse as either gamma-ray or neutron produced. It is estimated below that a sample containing ~ 60 grams of Pu-239 will emit ~ 10^7 gamma-ray quanta per second with energies greater than 200 keV. If a proton recoil scintillator were exposed directly to this gamma-ray flux then 10^5 to 10^6 gamma-ray pulses per second might be expected in each detector; this would result in serious dead time losses because of the time required to classify the pulses. The gamma-ray pulses could be reduced by differential filtering which, however, for a given size of scintillators will cause further reduction in neutron efficiency. In view of these anticipated difficulties, it is tentatively assumed that the proton-recoil scintillator approach will have limited usefulness.

GENERAL DISCUSSION

The equipment discussed in Case 1 was designed to be conveniently portable and was intended for the measurement of samples which were physically small. Considering the restraints which were applied, its performance is good. It remains true, however, that a rather long observation time is necessary if a precision of a few percent is to be obtained. If the neutron coincidence approach is to contribute effectively to the safeguards program, performance superior to that outlined for Case 1 is deemed necessary. It is anticipated that both portable equipments and one or more designs of more complex and powerful equipments in which performance is stressed at the expense of simplicity, portability, and cost will be desirable.

The requirement for reducing the observation time is an increase in efficiency generally associated with a reduction of neutron lifetime, gate length and equipment dead times. For smaller samples the efficiency increase is more important; as sources size increase both the efficiency and the lifetime, τ, and dead times are important. A careful balance of efficiency and lifetime is necessary in efforts to improve performance.

The efficiency of moderating detectors employing BF_3 neutron detection tubes can be increased considerably above that of Case 1 by using an increased active volume and increasing the ratio of BF_3 tube to moderator volume. Some advantage may be gained by surrounding the detector with a tailored reflector. Any fast or intermediate neutrons reflected back to the active volume should increase efficiency without increasing neutron lifetime appreciably; the reflection of thermal neutrons while increasing efficiency, will also increase lifetime. An active volume surrounded by cadimum or boral which in turn is surrounded with a reflector or alternatively a poissoned reflector surrounding the active volume is expected to improve overall performance.

To first approximation the use of BF_3 tubes should be equivalent to ^{3}He tubes provided the tubes have about the same neutron absorption characteristics and are equally efficient in producing a useful count for each neutron absorbed. Generally a higher efficiency can be obtained with ^{3}He than with BF_3 tubes due to a 40% larger thermal neutron absorption cross section and the feasibility of using higher gas pressures. East and Walton[9] estimate that 1 in. diameter BF_3 tubes filled to ~ 1.5 atmospheres pressure will yield an efficiency roughly 60% or less than that obtained with 4 to 6 atmosphere pressure 1 in. diameter ^{3}He tubes. Somewhat higher efficiencies are believed possible if 2 in. diameter BF_3 tubes are employed rather than 1 in. diameter tubes; the slower pulses from the 2 in. tubes may, however, lead to difficulties in maintaining an adequately short gross dead time. It seems reasonable to assume that efficiencies of 25% or perhaps greater can be obtained with BF_3 tube arrays. In any case, the use of BF_3 tubes is expected to yield a less costly detector.

An important consideration in equipment design is the gross channel dead time. For the conditions assumed in Case 1, dead time losses require correction for $m(1 + \alpha) \geq$ about 12.5 g. A shorter gross dead time would be desirable even at the assumed efficiency of 0.1. If higher efficiencies are obtained the dead time must be decreased at least proportionally if serious difficulties are to be avoided. According to Chase,[10] the gross dead time can not be reduced below about 6 μs if the present type of 2 in. diameter tubes are used. Presuming that Chase's analysis is correct, this type of BF_3 tube will have limited usefulness in higher efficiency detectors.

The A to N ratio which is important both as regards any R and A gate imbalance and as regards its impact on the observation time is to first order independent of the efficiency and proportional to the quantity $\tau m(1 + \alpha)$ provided τ is somewhat larger than ℓ. If the expediency is considered of shortening τ relative to ℓ in order to reduce the A to N ratio, the more explicit relation

$$\frac{A}{N} \approx \frac{\tau\, C^2\, (1 + \alpha)^2\, m}{C \left(\frac{E_s}{\epsilon\, E_f}\right) e^{-t_o/\ell} (1 - e^{-\tau/\ell})} \tag{22}$$

must be considered. $\left(\frac{E_s}{\epsilon\, E_f}\right)$ ranges from 0.9 to 0.58 as ϵ varies from 0 to 1.0 (Table A2) and $C \approx 10^3$ when τ is in seconds. Thus

$$\frac{A}{N} \approx \frac{1.3 \times 10^{3}\, \tau\, (1 + \alpha)^2\, m}{e^{-t_0/\ell}(1 - e^{-\tau/\ell})} \tag{23}$$

Reducing τ from say 1.2 ℓ to a very small value will only reduce A/N to 58% of its original value; simultaneously, however, N will be reduced by the factor $(1 - e^{-\tau'/\ell})/(1 - e^{-1.2})$ in which τ' is the new and shorter gate length.

The expected magnitude of A/N, assuming a specific measurement situation and a desired precision, will dictate the required similarity of R and A gates. The similarity required is important in choosing between gates generated by digital logic and gates produced by separate multivibrators; the use of a single multivibrator produced gate and steering logic used in the first Brookhaven equipment[11] is markedly inferior since it requires an analysis dead time of at least 2.5 times the gate length.

The use of a large liquid scintillator appears highly advantageous in several respects. The fact that the moderator is also the detector is highly advantageous; for this reason very high efficiencies concomitant with short neutron lifetimes become possible. The principal problems would appear to be discrimination against undesired pulses and the requirement, common to all high efficiency detectors, of reducing the dead time losses to a satisfactorily low value.

Neutron detection is possible either by capture in an element like cadimum and using the deexcitation gamma rays as the indication of the neutron's death as was done by Diven et al. or by capture in an isotope such as ^{10}B and using the scintillation caused by the charged particles emitted in the reaction. If a reaction emitting charged particles is employed the smaller specific scintillation response of charged particles compared to gamma-ray produced electrons would decrease the effectiveness of discrimination against gamma rays on the basis of pulse height alone. Further, the possibility of discrimination against gamma rays by pulse shape is probably not feasible because of the requirement of maintaining a gross dead time of a fraction of a μs and the high intensity of gamma rays expected from plutonium samples. About 2.7×10^4 quanta per second of 414 keV gamma rays are expected from one gram of Pu-239.[12] A crude guess based on a GeLi spectrum[13] indicates that perhaps 2×10^5 quanta per gram - sec with energies above 200 keV are to be expected. A thin sample containing 60 grams of Pu-239 (about the equivalent of one 2" x 4" PNC plate fabricated by NUMEC) would emit $\sim 10^7$ quanta per second with energies above 200 keV. Since some period of time (characteristically a μs or so) is required to classify a pulse, the losses of the desired neutron pulses is expected to be intolerable for a wide range of plutonium samples. Although differential shielding could be used to reduce the gamma rays relative to the neutrons, the prospect of using pulse shape discrimination effectively seems poor.

The possibility exists that a single neutron can cause two pulses; the first from the recoil protons and possibly gamma rays associated with the slowing down of a fast neutron and the second from the neutron capture reaction. For proper operation the first pulse must be strongly discriminated against since otherwise single neutrons from (α,n) reactions could result in an unacceptable false coincidence indication.

The approach of using the deexcitation gamma-ray pulses as indications of neutron captures would appear less problematic in several respects. The kinetic energy of fast neutrons is expected to be largely dissipated via recoil protons and because of non-linear scintillator response the resulting pulse height is expected to be small compared to that resulting from the deexcitation gamma rays. One disadvantage is that a larger scintillator is likely to be required for a given efficiency due to the mean free paths of the deexcitation gamma rays being very large compared to the range of charged particles.

A crude estimate of about 10^3 background pulses per second larger than the threshold used by Diven et al. is possible from the data of Table 1 of their paper and an estimate of the length of the oscilloscope traces used based upon the statement that 2% of the pulses occurred after the end of the trace.[5] This background would not preclude useful measurements. (The bias was such that about 85% of the neutron captures in cadmium produced usable pulses.)

Diven et al. used the occurrance of a fission in a fission chamber to start an oscilloscope trace on which pulses from the large scintillator were displayed. In "at least 99% of the fission events" a pulse was observed due to prompt fission gamma rays. In their experiment these pulses occurred at a fixed position on the oscilloscope trace and were used to assure that the trace was indeed triggered by a fission event.

It is not clear what fraction of these pulses were larger than the discriminator level employed. In considering fissometer operation, any prompt fission gamma-ray pulses larger than the discriminator level employed would have the effect of increasing the coincidence signal. For thin samples from which the fission gamma rays escape this might be a valuable effect, however, with samples of considerable thickness, self absorption would reduce the probability of prompt fission gamma-ray pulses and some difficulty in the interpretation of the measurements would result. This effect can be reduced by a lead filter between source and scintillator, a measure which may be required to reduce gamma-ray pile up. The $\sim 10^7$ quanta per second with energies above 200 keV calculated above may, in the absence of shielding, lead to gamma-ray pile up pulses larger than the discriminator level. Also the measurement of larger samples is to be anticipated for which the pile up difficulty will be worse. A lead shield 1 cm thick should reduce the gamma-ray intensity by more than a factor of ten. Pending a more reliable analysis, a shield of a few cm of lead will be assumed; in a 4π detector this thickness of lead should have little effect on the source neutrons.

DISCUSSION OF SPECIFIC EQUIPMENTS

The question of how much improvement in neutron coincidence equipment is worth paying for will hinge upon the performance expected in plutonium assay measurements. Hence some specific examples are worth exploring.

Table 1 shows predicted performance for the latest Brookhaven equipment discussed above as Case 1. The ratio of nonfission to fission neutron counts (α) is arbitrarily taken as unity. This yields slightly pessimistic results for many fuel compositions including the SEFOR PuO_2-UO_2 fuel, however, the predictions may be optimistic for other samples.

For Case 1 the calculated gross dead time loss becomes 1% for $m(1 + \alpha) = 12.5$ and hence the predicted performance shown for 10 g of Pu-240 would require an appropriate correction (about 3% applied to N) and the performance for m = 100 should be considered specious for this equipment; it is included to show what performance would result if the dead time problem were solved.

A second criterion on the gross dead time has been arbitrarily set by the relation $t_1 \leq 0.1\ \Delta$. Since the effective value of t_o will of necessity be equal to or larger than t_1 this criterion corresponds to a reduction in the value of the net count of about 10% below what might be obtained were t_1 and t_o both equal to zero. A design consideration not previously discussed is that t_o should be made a little larger than t_1 in order to avoid an imbalance between the lengths of the R and A gates; no pulse can transit the gross channel until a time equal to or larger than t_1 following the pulse which initiates the analysis cycle.

The long 1% observation times shown (more than one hour) points up the need of more powerful equipment; both a reduction in neutron lifetime, gate length and dead times, and an increase in efficiency are indicated.

The predicted performance for Case 2 is shown in Table 2, using ϵ = 0.4 and Δ = 30 rather than the slightly different values quoted above. The calculated observation times necessary for a 1% statistical standard deviation are quite reasonable for m = 1, 10 and 100. The rather large A/N ratio for larger values of m may lead to errors in actual equipment.

The predicted performance for Case 3 is shown in Table 3. The calculated 1% observation times are quite short implying that this powerful a detector is not required. The A/N ratios are roughly half those for Case 2 and the required values of t_1, τ and t_2 are just half those of Case 2.

The Case 2 and Case 3 examples were chosen as approximately the best performance which can be expected with the techniques involved. In considering the plutonium assay problem somewhat less powerful and less expensive detectors are likely to be preferable. From the infinite combinations of parameter values, a few illustrative examples may be helpful.

Table 4 shows the predicted performance of Case 4 for which ϵ = 0.2, $\tau = t_2$ = 20 μs, and Δ = 15 μs is assumed. It is anticipated that approximately these parameters could be obtained by a smaller liquid scintillator employing the same composition of scintillating fluid. It is presumed that roughly these parameters could be obtained with ^{3}He or BF_3 tubes in a moderating medium. If the neutron leakage from the large LASL detector is small, then this performance could be obtained, albeit very inefficiently, by judicious poissoning. Detectors with somewhat smaller active volumes and perhaps some poissoning should approximate this condition.

In Case 4 the 1% observation times are reasonably short and the A/N ratio and the required gross dead time for large samples are reduced roughly a factor of two from those of Case 2; the A/N ratio is comparable to Case 3; however, the requirement on gross dead time for large samples is relaxed by a factor of 4.

The large A/N ratios predicted for $m = 100$ in all cases considered is expected to cause difficulty in actual practice. This ratio can in principal be reduced by reducing τ. As mentioned above a reduction of τ without a reduction in ℓ will not reduce this ratio by more than about 40%, hence a simultaneous reduction of both ℓ and τ is expected to be advisable. Table 5 shows predicted performance for $\epsilon = 0.2$, $\tau = t_s = 10\ \mu s$, $t_o = 0$ and $\ell = 9\ \mu s$. The predicted performance for this case is in general superior to that for Case 4. The A/N ratio, however, has only been reduced by a factor of 2 and excellent similarity of R and A gates will be required if accurate measurements are to be made for $m = 100$ and $\alpha = 1$. A difference of 1 part in 10^3 in the lengths of the R and A gates would lead to roughly a 1% error in the deduced value of N.

CONCLUSION

In the design of the existing Brookhaven built equipments, considerable emphasis was placed upon portability. The performance achieved is near optimum in light of the restraints which were applied. It seems clear, however, that if rapid and precise coincidence assay measurements of plutonium are to be made, more powerful (and more costly) equipments will be required.

Improved performance will require the development of detectors with higher efficiencies and shorter neutron lifetimes than those displayed by the Brookhaven built equipments. Simultaneous changes in the analysis electronics will be required. The reduction of the neutron lifetime cannot be capitalized upon unless the analysis gate length is adjusted to a valve about equal to or only slightly longer than the neutron lifetime. Concomitant with the higher efficiency and shorter neutron lifetime, a considerable reduction in gross channel dead time will be required.

The two more promising approaches to detectors with higher efficiencies and shorter lifetimes appear to be the use of moderating detectors with larger active volumes than those in the present Brookhaven built equipments and the use of a fairly large 4π liquid scintillation detector perhaps similar in method of operation to the one used by Diven et al.[5] but with somewhat smaller dimensions. Work at Los Alamos has shown that very useful efficiencies and neutron lifetimes can be obtained in detectors of the first type.[4] One question not clear from reports of the Los Alamos work is whether short enough detector dead times are achievable. In principal, comparable efficiencies and neutron lifetimes should be obtainable with enriched BF_3 detector tubes. Some doubt, however, exists as to whether adequately short detector and amplifier dead times can be achieved.

The approach of using a 4π liquid scintillator appears very promising in principal. The fact that the scintillator is both the moderator and the neutron detection medium implies that higher efficiencies along with perhaps adjustable neutron lifetimes are possible. A question not resolved is whether the detection of the desired neutron-capture pulses along with adequate discrimination against unwanted pulses will be possible. Also, the complexity and cost of this type of a detector may be a deterring factor. A further investigation of this approach seems indicated.

REFERENCES AND NOTES

1. Early fissometer work is summarized by R. J. Omohundro and W. A. Marchetti in NRL Memorandum Report 2005 (1969); a later summary by C. V. Strain and R. J. Omohundro is found in NRL Memorandum Report 2107 (1970).

2. The neutron lifetime would logically be the average time interval between the birth and the death of a neutron. For fissometer operation the parameter of interest is the average time interval between the first of two or more counts produced by a single fission and the following counts, this parameter is designated as the differential lifetime. For convenience an exponential differential lifetime is assumed which is appropriate for the Brookhaven built fissometer detectors. A more complicated dieaway characteristic can be used if deemed appropriate.

3. E. V. Weinstock (Brookhaven) private communication.

4. LA-4315-MS, pp 21-22 (1969)

5. B. C. Diven, H. C. Martin, R. F. Taschek, and J. Terrell, Phys. Rev. 101, 1012 (1956).

6. J. B. Marion and J. F. Fowler, Fast Neutron Physics, Part II, page 2032, Interscience Publishers, New York and London (1963).

7. C. Sastre of Brookhaven, private communication.

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10. R. L. Chase of Brookhaven via W. A. Higinbotham, private communication.

11. C. V. Strain and R. J. Omohundro, NRL Memorandum Report 2107, pp. 6-8 (1970)

12. W. A. Higinbotham, private communication.

13. Spectrum taken by E. V. Weinstock, private communication.

Table 1. Predicted Performance; Case 1* with $\alpha = 1$.

Item	Mass of Pu-240		
	1	10	100
1. Maximum value of t_1 (μs)			
a) $t_1 < \frac{10}{\epsilon\, m(1+\alpha)}$	50	5**	0.5**
b) $t_1 < 0.1\, \ell$	9	9	9
2. A/N	0.87	8.75	87.5
3. $t(1\%, m)$			
a) 1st term	29.1	2.9	0.3
b) 2nd term	52.4	52.4	52.4
c) 3rd term	1.4	14.4	143.7
d) $t(1\%, m)$	82.9	69.7	196.4
4. F_ℓ (per sec)	200	2000	2×10^4
5. N_ℓ (per sec)	5.7	57	570

*Parameters assumed are $\epsilon = 0.1$, $t_1 = 8\ \mu s$, $\tau = 129\ \mu s$, $t_s = 138\ \mu s$ and $\ell = 90\ \mu s$.

**Criterion not satisfied by present equipment.

Table 2. Predicted Performance; Case 2* with $\alpha = 1$.

Item	Mass of Pu-240		
	1	10	100
1. Maximum value of t_1 (μs)			
a) $t_1 < \frac{10}{\epsilon\, m(1+\alpha)}$	12.5	1.25	0.125
b) $t_1 < 0.1\,\ell$	3.0	3.0	3.0
2. A/N	0.288	2.88	28.8
3. $t(1\$,m)$			
a) 1st term	2.08	0.21	0.02
b) 2nd term	1.33	1.33	1.33
c) 3rd term	0.04	0.43	4.26
d) $t(1\$,m)$	3.45	1.97	5.61
4. E_ℓ (per sec)	800	8×10^3	8×10^4
5. N_ℓ (per sec)	80	8×10^2	8×10^3

*Parameters assumed are $\epsilon = 0.4$, $\tau = 40\ \mu s$, $t_s = 40\ \mu s$ and $\ell = 30\ \mu s$

Table 3. Predicted Performance; Case 3* with $\alpha = 1$.

Item	Mass of Pu-240		
	1	10	100
1. Maximum value of t_1 (μs)			
a) $t_1 < \dfrac{10}{\epsilon\, m(1+\alpha)}$	6.25	0.625	0.0625
b) $t_1 < 0.1\, \ell$	1.5	1.5	1.5
2. A/N	0.158	1.58	15.8
3. t(1%,m)			
a) 1st term	0.618	0.062	0.006
b) 2nd term	0.235	0.235	0.235
c) 3rd term	0.007	0.075	0.751
d) t(1%,m)	0.860	0.372	0.992
4. E_ℓ (per sec)	1,600	1.6×10^4	1.6×10^5
5. N_ℓ (per sec)	270	2.7×10^3	2.7×10^4

*Parameters assumed are $\epsilon = 0.8$, $\tau = 20$ μs, $t_s = 20$ μs and $\ell = 15$ μs.

Table 4. Predicted Performance; Case 4* with α = 1.

Item	Mass of Pu-240		
	1	10	100
1. Maximum value of t_1 (μs)			
a) $t_1 < \frac{10}{\epsilon m(1+\alpha)}$	25	2.5	0.25
b) $t_1 < 0.1\,\ell$	1.5	1.5	1.5
2. A/N	0.138	1.38	13.8
3. t(1%,m)			
a) 1st term	7.60	0.76	0.08
b) 2nd term	2.22	2.22	2.22
c) 3rd term	.02	.18	1.78
d) t(1%,m)	9.84	3.16	4.08
4. E_ℓ (per sec)	400	4000	4×10^4
5. N_ℓ (per sec)	22	220	2.2×10^3

*Parameters assumed are ϵ = 0.2, $\tau = t_s$ = 20 μs and ℓ = 15 μs

Table 5. Predicted Performance; Case 5* with $\alpha = 1$.

Item	Mass of Pu-240		
	1	10	100
1. Maximum value of t_1 (μs)			
a) $t_1 < \frac{10}{\epsilon\, m(1 + \alpha)}$	25	2.5	0.25
b) $t_1 < 0.1\, \ell$	0.9	0.9	0.9
2. A/N	0.068	0.68	6.78
3. $t(1\%, m)$			
a) 1st term	7.60	0.76	0.08
b) 2nd term	1.11	1.11	1.11
c) 3rd term	.00	.04	0.44
c) $t(1\%, m)$	8.71	1.91	1.63
4. E_ℓ (per sec)	400	4000	4×10^4
5. N_ℓ (per sec)	22	220	2.2×10^3

*Parameters assumed are $\epsilon = 0.2$, $\tau = t_s = 10\ \mu s$ and $\ell = 9\ \mu s$.

APPENDIX A

Relations for Predicting Fissometer Performance

In the following an approach is used which is more conveniently applicable to fissometers with high efficiency detectors than the approach previously used.[A1]

The ideal gross count rate, E_l, for a sample in which both Pu-240 spontaneous fission and (α,n) reactions are occurring is taken as

$$E_l = C\, m(1 + \alpha)\, \epsilon \qquad (A1)$$

in which m is the mass of Pu-240 in grams, α is the ratio of nonfission counts to fission-neutron-produced counts, ϵ is the detector efficiency in counts per source neutrons and C is a constant equal to the spontaneous fission rate per gram times the average number of neutron per fission. For convenience $C = 10^3$ per second is assumed (this value is perhaps ~ 2% low).

An important relation for the analysis of fissometer performance is the fraction of the gross pulses which may be designated as subsequent or following pulses; these are the second pulse of a pair produced by a single fission, the second and third of three counts produced by a single fission, etc.

Defining the probability of ν prompt neutrons being emitted in a single fission event as Q_ν, taking ϵ as the probability that a prompt neutron will produce a pulse and defining $q \equiv 1 - \epsilon$, the probability that no pulse will be produced by a fission is

$$P_o = \sum Q_\nu \, q^\nu \tag{A2}$$

and in general, the probability of n pulses being produced by one fission is

$$P_n = \sum \binom{\nu}{n} Q_\nu \, \epsilon^n \, (1 - \epsilon)^{\nu - n} \tag{A3}$$

in which $\binom{\nu}{n}$ is the binomial coefficient; i.e. $\binom{\nu}{n} = \nu!/n!(\nu - n)!$.

The average number of counts per fission is given by

$$E_f = \sum n \, P_n. \tag{A4}$$

From eqs. (A3) and (A4) and using an additional index,

$$E_f = \sum k \, P_k = \sum_k k \sum_{\nu = k} \binom{\nu}{k} Q_\nu \, \epsilon^k \, (1 - \epsilon)^{\nu - k}. \tag{A5}$$

When expanded in terms of powers of ϵ, all terms but the first are zero and

$$E_f = \epsilon \sum_\nu \binom{\nu}{k} Q_\nu = \epsilon \, \bar{\nu}. \tag{A6}$$

The average number of following counts per fission is given by

$$E_s = \sum (n - 1) \, P_n = \sum_{n=2} n \, P_n - \sum_{n=2} P_n. \tag{A7}$$

Noting that

$$\sum_{n=2} n P_n = \sum_{n=1} n P_n - P_1 = \epsilon \bar{\nu} - P_1 \tag{A8}$$

and that

$$\sum_{n=2} P_n = 1 - P_o - P_1 \tag{A9}$$

.

$$E_s = \bar{\nu} \epsilon - 1 + P_o. \tag{A10}$$

An alternate relation, which usually is more appropriate for small values of ϵ, is obtained by expressing E_s in terms of the Q_ν's and powers of ϵ.

$$E_s = \sum_{k=2} (k - 1) P_k = \sum_{k=2} (k - 1) \sum_{\nu=k} \binom{\nu}{k} Q_\nu \epsilon^k (1 - \epsilon)^{\nu-k}. \tag{A11}$$

Expanding and collecting in terms involving powers of ϵ yields

$$E_s = \sum_{n=2} (-1)^n M_n \epsilon^n \tag{A12}$$

in which

$$M_n = \sum \binom{\nu}{n} Q_\nu . \tag{A13}$$

The M_n's are averages of functions of ν, the variable number of prompt neutrons emitted in fission, with

$$M_1 = \langle \nu \rangle = \bar{\nu} \tag{A14a}$$

$$M_2 = \frac{\langle \nu(\nu - 1) \rangle}{2!} \tag{A14b}$$

$$M_3 = \frac{\langle \nu(\nu - 1)(\nu - 2) \rangle}{3!} \tag{A14c}$$

etc. In this analysis, the delayed neutrons have been ignored; they can be included in the α of equations such as (A1) if desired.

Using values of the Q_ν's listed in Table A1, which are believed adequately representative of Pu-240,[A2] ratios of E_s to E_f have been computed for several values of ϵ. The two approaches, namely

$$\frac{E_s}{E_f} = 1 - \frac{(1 - P_o)}{\bar{\nu}} \tag{A15}$$

obtained from eqs. (A6) and (A10) and

$$\frac{E_s}{E_f} = \frac{1}{\bar{\nu}} \sum_{n=2} (-1)^n M_n \epsilon^{n-1} \tag{A16}$$

obtained from eqs. (A6) and (A12) yield the same results when the value of the M_n's calculated from the assummed values of the Q_ν's shown in Table A1 are used. Values of E_s/E_f are shown in Table A2.

Also shown is the ratio $E_s/\epsilon\, E_f$ which is a more slowly varying function of ϵ than is E_s/E_f.

In predicting fissometer performance, the ideal gross count rate is given by eq. (A1). The observed gross count rate, E, will be less than E_l due to gross channel dead time, t_1. Assuming that $t_1 \ll \ell$ (ℓ is the differential neutron lifetime in the detector), it is assumed that

$$E = \frac{E_l}{1 + t_1\, E_l} \,. \tag{A17}$$

To avoid awkward equations in the following analysis, it is assumed that gross dead time losses are unimportant and that $E = E_l$. However, eq. (A17) is used above in considering the errors in the observed value of the net (coincidence) count rate due to a given value of t_1 and E_l.

The component of E due to fission neutron is $C\, m\, \epsilon$. Assuming that in fissometer operation the time between the arrival of a pulse which initiates an analysis cycle and the opening of the R gate is t_0, the length of the R gate is τ, and the differential neutron lifetime in the detector is ℓ, the ideal net count rate is taken as

$$N_l = C\, m\, \epsilon \left(\frac{E_s}{E_f}\right) e^{-t_0/\ell}\, (1 - e^{-\tau/\ell}) \tag{A18}$$

in which E_s/E_f is given by eq. (A15) or (A16).

For reason of simplicity, it will be assumed that at slow counting rates the analysis cycle rate (the number of pairs of gates per unit time) will be

$$G_l = E - N_l. \tag{A19}$$

(This relation is correct when $t_o = 0$.) Ignoring the complicating fact that the spacing of pulses included in G_l is not randomly distributed in time, it is assumed that

$$G = \frac{G_l}{1 + t_s\, G_l} = \frac{E - N_l}{1 + t_s(E - N_l)} \tag{A20}$$

in which t_s is the analysis cycle dead time. The accidental count rate, A, is taken as

$$A = \tau\, G\, E = \frac{\tau\, E(E - N_l)}{1 + t_s(E - N_l)} \tag{A21}$$

and the observed net count rate, N, is taken as

$$N = \frac{N_l}{1 + t_s(E - N_l)} \quad . \tag{A22}$$

The count rate observed in the R channel is obtained from R = A + N.

A ratio of considerable importance if any dissimilarity between the number or lengths of the R and A gates is

$$\frac{A}{N} = \frac{\tau\, E(E - N_{\ell})}{N_{\ell}} . \qquad \text{(A23)}$$

The observation time necessary to obtain a given statistical standard deviation in the measured value of N is important in comparing the performance of different equipments. Using an approximate relation which ignores the fact that R and A are not independent random variables[A3] it will be assumed that the observation time necessary to obtain a 1% standard deviation of the net count rate N is given by

$$t(1\%) = \frac{10^4(R + A)}{N^2} = \frac{10^4\left(1 + \frac{2A}{N}\right)}{N} . \qquad \text{(A24)}$$

More useful relations are obtained when A/N and t(1%) are expressed in terms of sample and equipment parameters. Employing eqs. (A1) and (A18) and defining

$$R_s = \frac{C}{C\left(\frac{E_s}{s\, E_f}\right) e^{-t_0/\lambda} \left(1 - e^{-\tau/\lambda}\right)} \qquad \text{(A25)}$$

eq. (A23) becomes

$$\frac{A}{N} = \tau\, C\, (1 + \alpha)\, [R_s(1 + \alpha) - \epsilon]\, m \le \tau\, C\, R_s(1 + \alpha)^2\, m$$

and eq. (A24) becomes

$$t(1\%) = \frac{10^4 R_s}{C \epsilon^2 m} + \frac{2 \times 10^4 \tau R_s (1 + \alpha)}{\epsilon^2} [R_s(1 + \alpha) - \epsilon]$$

$$+ \frac{10^4 t_s}{\epsilon} [R_s(1 + \alpha) - \epsilon]$$

$$+ \frac{2 \times 10^4 \tau t_s}{\epsilon} C(1 + \alpha)[R_s(1 + \alpha) - \epsilon]^2 m. \qquad \text{(A27)}$$

For equipment with $t_o/\ell = 0$ and $\tau/\ell = 1.1$, the applicable R_s values are given in Table A2. R_s varies monotonically from 1.7 for $\epsilon = 0$ to 2.59 for $\epsilon = 1.0$. Hence eqs. (A26) and (A27) are in a form which exhibits the principal variation of observation time with ϵ, τ and t_s provided t_o/ℓ and τ/ℓ are fixed.

For a well designed equipment $t_s \approx \tau$, then eq. (A27) becomes

$$t(1\%) = \frac{10^4 R_s}{C \epsilon^2 m} + \frac{10^4 \tau}{\epsilon^2} [2R_s(1 + \alpha) + \epsilon][R_s(1 + \alpha) - \epsilon]$$

$$+ \frac{2 \times 10^4 \tau^2 C_1 (1 + \alpha)}{\epsilon} [R_s(1 + \alpha) - \epsilon]^2 m. \qquad \text{(A28)}$$

REFERENCES AND NOTES

A1. C. V. Strain and R. J. Omohundro, NRL Memorandum Report 2107 (March 1970)

A2. The Q_ν values are based upon the distribution given by G. R. Keepin, Physics of Nuclear Kinetics, (Addison-Wesley Publishing Co. Inc., Reading, Mass., 1956) p. 60. The values obtained agree well with Diven et al., Phys. Rev. 101, 1012 (1956). The value of $\bar{\nu}$ = 2.256 calculated from the Q_ν's is 2 to 3% larger than the values given by Keepin (page 53).

A3. Pages 42 and 43 of reference A1.

Table A1. Assumed Values of Q_ν and Calculated Values of M_n.

ν	Q_ν	n	M_n
0	0.052,7	1	2.256,1
1	0.191,8	2	2.027,2
2	0.345,7	3	0.906,1
3	0.286,2	4	0.212,08
4	0.105,0	5	0.025,84
5	0.017,27		
6	0.001,28	6	0.001,58
7	0.000,40		
8	5.6×10^{-7}	7	0.000,045
9	3.4×10^{-9}		
10	9.0×10^{-11}	8	5.95×10^{-7}

Table A2. Calculated Values of E_s/E_f and $E_s/\epsilon E_f$

ϵ	E_s/E_f	$E_s/\epsilon E_f$	R_s*
0.	0	0.8985	1.669
0.05	0.043,93	0.8787	1.707
0.1	0.085,93	0.8599	1.746
0.15	0.126,05	0.8404	1.785
0.2	0.164,37	0.8218	1.825
0.25	0.200,96	0.8038	1.866
0.3	0.235,86	0.7862	1.908
0.4	0.300,88	0.7522	1.994
0.5	0.359,89	0.7198	2.084
0.6	0.413,41	0.6890	2.177
0.7	0.461,78	0.6597	2.274
0.8	0.505,45	0.6318	2.374
0.9	0.544,78	0.6053	2.478
1.0	0.580,00	0.5800	2.586

$$*R_s = \frac{1.5\,\epsilon\,E_f}{E_s}$$

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13. ABSTRACT

Coincident neutron detectors which can distinguish between neutrons occurring as a result of fission and those due to (α,n) or (γ,n) nuclear reactions have been described in a preceding report. (NRL Memorandum Report 2107). ~~In this~~ The report discusses several methods of developing follow-on equipments with greater potential for the nondestructive assay of plutonium samples. ~~are examined~~. The effect on equipment performance of the efficiency and neutron lifetime in the neutron detector and of analysis gate length and equipment dead times are treated in considerable detail and several illustrative examples are presented. Performance is generally improved by an increase of neutron efficiency accompanied by a decrease in neutron lifetime and the use of optimized analysis circuitry. Good performance can be obtained with complex 4π moderating detectors which employ an array of enriched BF_3 or ^{3}He neutrons detection tubes dispersed in a hydrogeneous moderator. The use of a large liquid scintillation detector may be an ideal approach if adequate discrimination against interfering pulses can be obtained.

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Nondestructive assay of plutonium						
Nuclear material safeguards						
Coincident neutron equipments						
Moderating neutron detectors						
Liquid scintillation neutron detectors						