A METHOD OF IMPROVING THE FRACTIONAL STANDARD DEVIATION IN THE COUNT RATE FOR AN NM-64 NEUTRON SUPERMONITOR

by

PADRAIG AUSTIN COUGHLAN

B.Sc., University College, Dublin, 1963

A THESIS SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

in the Department
of
Physics

We accept this thesis as conforming
to the required standard

[redacted]

[redacted]

[redacted]

[redacted]

Accepted by the Faculty of Graduate Studies

on May 7, 1968 by [redacted] Dean of Faculty

UNIVERSITY OF VICTORIA
April 1968

ABSTRACT

Supervisor: Dr. G. R. Mason

Neutron monitors are commonly used to investigate small fluctuations in the nucleonic component of cosmic rays at sea level. The monitors achieve a high counting rate by using a lead target to produce multiple evaporation neutrons. However, the large variations in the number of neutrons per evaporation result in a non-Poissonian distribution of the count rate. An experimental method of detecting only the randomly distributed nuclear disintegrations has been devised.

The evaporation neutrons are produced in bursts well separated in time so that the detector can be made sensitive only to bursts by the use of an appropriate dead time. For the NM-64 monitor the use of a 1200 microsecond dead time improves the fractional standard deviation by 18 percent.

TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

ACKNOWLEDGMENTS

I would like to acknowledge the assistance and advice provided by my supervisor, Dr. G. R. Mason, who designed the dead time unit used in this work.

I am also indebted to Dr. R. M. Pearce for valuable discussions and for his help in resolving some of the difficulties encountered during the course of the work.

I. INTRODUCTION

Continuous monitoring of the nucleonic component of the secondary cosmic radiation is being carried out at the University of Victoria using an NM-64 neutron supermonitor. The NM-64 supermonitor was designed by H. Carmichael (Hatton and Carmichael, 1964). It has a higher counting rate than the IGY neutron monitor designed by Simpson et al, 1953 and therefore is very satisfactory for the examination of small variations in the nucleon component of the secondary cosmic ray intensity. The high counting rate results from the production of multiple evaporation neutrons in the lead of the monitor by nuclear interactions of the secondary cosmic rays. There are on an average eight evaporation neutrons produced per interacting secondary (Bercovitch et al, 1960).

Because the number of evaporation neutrons produced per interaction varies between wide limits, the fluctuations in the count rate do not have a Poisson distribution. It has been found (Hatton and Carmichael, 1964) that the standard deviation in the count rate is larger than would be predicted from Poisson statistics. Since much of the work being done with the NM-64 supermonitor deals with very small modulations it is desirable to keep the fractional standard deviation as small as possible.

The purpose of the present work is to minimize the fractional standard deviation by counting only the nuclear disintegrations in the lead which do have a Poisson distribution. Since each nuclear disintegration is accompanied by a burst of evaporation neutrons and since these bursts are well spaced in time, it is possible to count only disintegrations by increasing the dead time of the counters to an appropriate value. This value depends on the mean life of the evaporation neutrons in the monitor which in turn depends on the geometry of the monitor.

The monitor has six proportional counters filled with boron triflouride gas isotopically enriched to 96% B^{10}. Each counter is surrounded by a cylinder of polyethylene 3/4" thick, called the inner moderator, the purpose of which is to moderate neutrons to thermal energies to facilitate their capture by the boron trifluoride. Surrounding the polyethylene are lead cylinders, and between them more lead, all of which acts as the main source of neutrons within the monitor (see Fig. 1). Surrounding the counters and lead is a polyethylene enclosure which acts as a reflector and moderator of evaporation neutrons, as a moderator of cosmic ray nucleons, and as a shield against low energy neutrons from the atmosphere and from local sources.

Because of the large size of the monitor the evaporation neutrons can have life times of many hundred microseconds before being captured by the counters. To ensure that only the first evaporation neutron of a burst is detected it is necessary to impose a relatively long dead time (of the order of 1000 microseconds) on the counters. Although there is a loss of counts with a long dead time a correction factor can be used to correct for this loss. This factor is a function of the count rate and can be incorporated into existing computer programs without much difficulty.

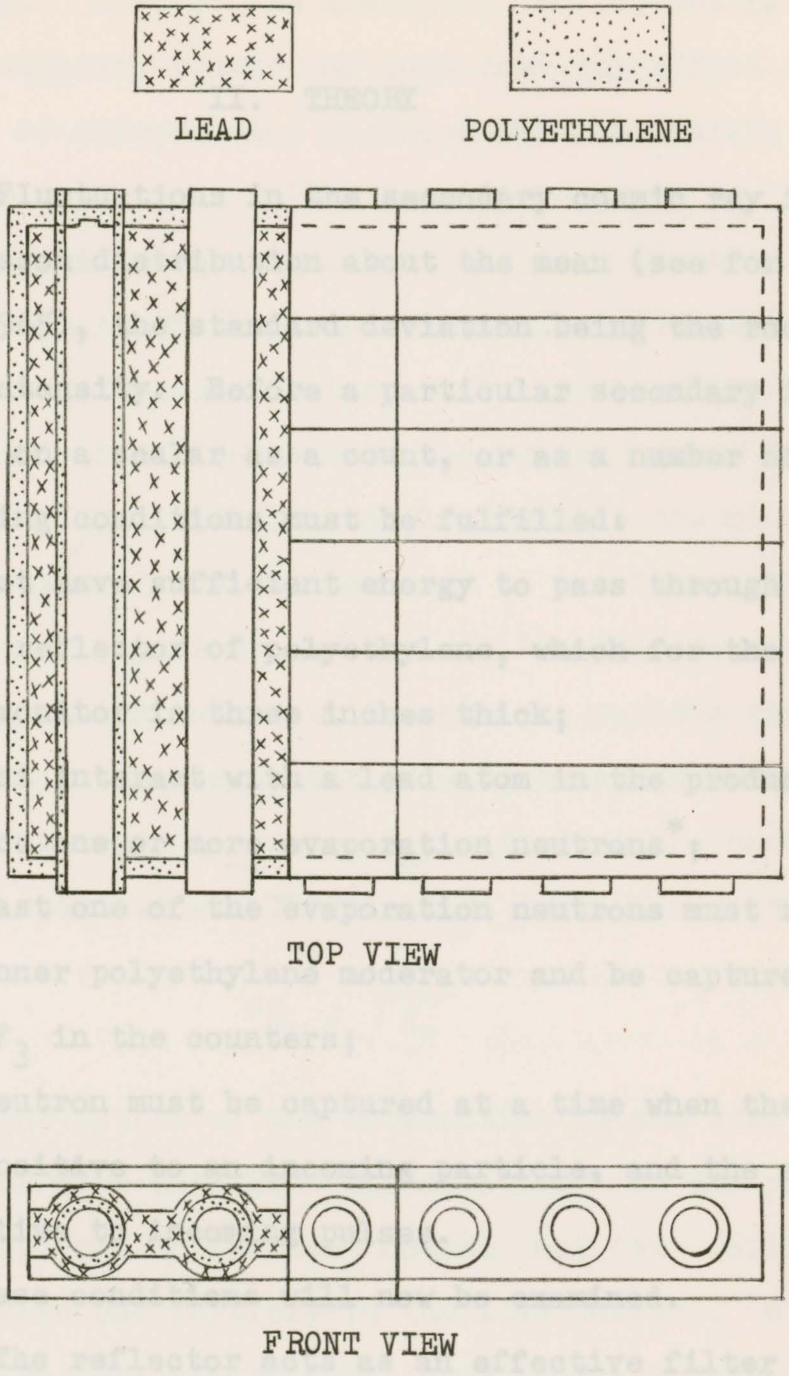


Fig. 1

Diagram of a typical 6 counter unit
of the NM-64 neutron supermonitor

II. THEORY

Fluctuations in the secondary cosmic ray intensity have a Poisson distribution about the mean (see for example Janossy, 1965), the standard deviation being the root of the mean intensity. Before a particular secondary is registered on a scalar as a count, or as a number of counts the following conditions must be fulfilled:

(a) it must have sufficient energy to pass through the outer reflector of polyethylene, which for the NM-64 supermonitor is three inches thick;

(b) it must interact with a lead atom in the producer and produce one or more evaporation neutrons*;

(c) at least one of the evaporation neutrons must reach the inner polyethylene moderator and be captured by the BF_3 in the counters;

(d) the neutron must be captured at a time when the counter is sensitive to an incoming particle, and the scalar sensitive to incoming pulses.

Each of these conditions will now be examined.

The reflector acts as an effective filter for low energy secondaries and moderates those secondaries which

---

*The total interacting component consists of 92% nucleons, 7% muons, and a remainder of pions and showers. Only the nucleonic part will be discussed here.

pass through. However the absorption of low energy nucleons from the secondary cosmic ray beam does not affect the randomness or independence of those which penetrate the reflector.

Consider now condition (b), i.e. the necessity for an interaction in the lead to occur. The processes involved are quite complicated, as the probability for an interaction to occur depends on the energy of the incident nucleon, on the distribution of lead within the monitor, and on the type of nucleon involved in the interaction (Metropolis et al, 1958). It is not feasible to perform calculations which take into account the various types of interactions in the lead, but it will be assumed that the averaged disintegration rate, N_E, satisfies the conditions of Poisson statistics. The standard deviation is therefore

$$\sigma_{N_E} = \sqrt{N_E} \quad . \tag{1}$$

The nature of the interaction in the lead will now be given more detailed consideration. In the process of being captured an incident nucleon may have collisions with more than one particle in the lead nucleus. Since the target particles have much lower energy and shorter mean free path than the incident nucleon they can escape from the nucleus without further collisions only if the first collision occurs near the edge of the nucleus with the struck particles heading out (Serber, 1947).

Otherwise they will collide with other nuclear particles, the energy will be distributed over the nucleus, and the subsequent events are described in terms of the evaporation model. The nuclear excitation energy is then dissipated by successive boiling off of particles each with a few MeV energy. The evaporation process has been extensively dealt with both theoretically (Metropolis et al, 1960; Dostrovsky et al, 1958;) and experimentally (Cocconi et al, 1950; Geiger, 1956; Bercovitch et al, 1960). The following results have been found:

(i) the mean number of evaporation neutrons produced per interaction in the lead (i.e. the mean multiplicity) increases with increasing energy of the incoming nucleon, and

(ii) for a given energy of incident nucleons (or more correctly for a given energy range of incident nucleons (see Hughes et al, 1964)) there is a distribution of multiplicities.

The evaporation neutrons do not constitute a set of independent events. It is therefore necessary to modify the Poisson equations for the standard deviation and fractional standard deviation. Before doing this the efficiency of the monitor for detecting evaporation neutrons (condition (c)) will be examined.

Pearce and Fowler, 1964, have used a computer program developed for reactor shielding to calculate the efficiency of detecting neutrons from disintegrations within the monitor. Their results are shown in Fig. 2.

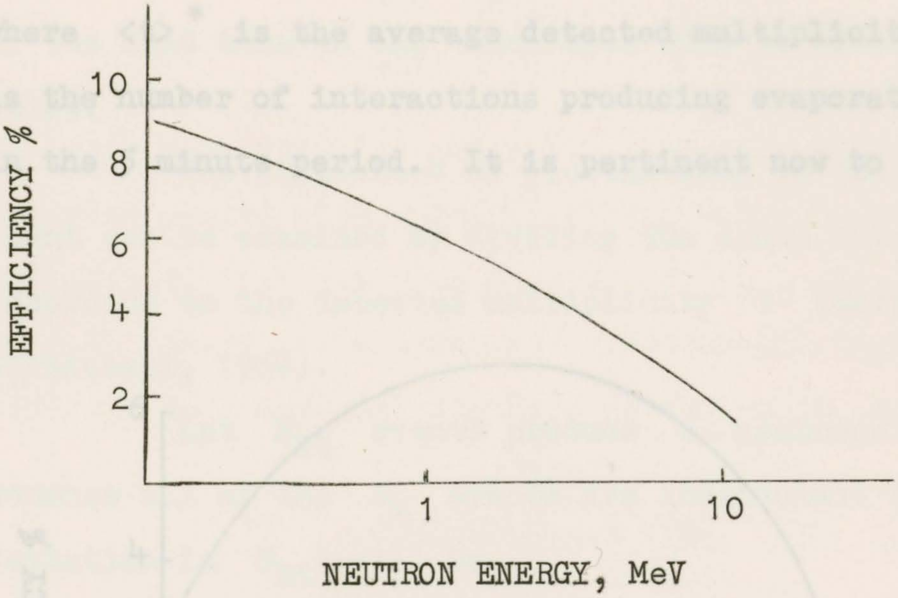


Fig. 2

Calculated efficiency for detecting evaporation neutrons as a function of neutron energy for NM-64 neutron monitor (Pearce and Fowler, 1964).

Hatton and Carmichael, 1964, have shown that the efficiency is also a function of the region in the lead where a nuclear interaction takes place (Fig. 3).

Assuming an average evaporation neutron energy of 2 MeV and following Hatton and Carmichael, 1964, an average efficiency can be assigned to the monitor. This average efficiency will be assumed to be a constant of the monitor. The number of detected neutrons per 5 minute interval will therefore be

$$N = N_E <t> \qquad (2)$$

where $<t>$ * is the average detected multiplicity and N_E is the number of interactions producing evaporation neutrons in the 5 minute period. It is pertinent now to examine the

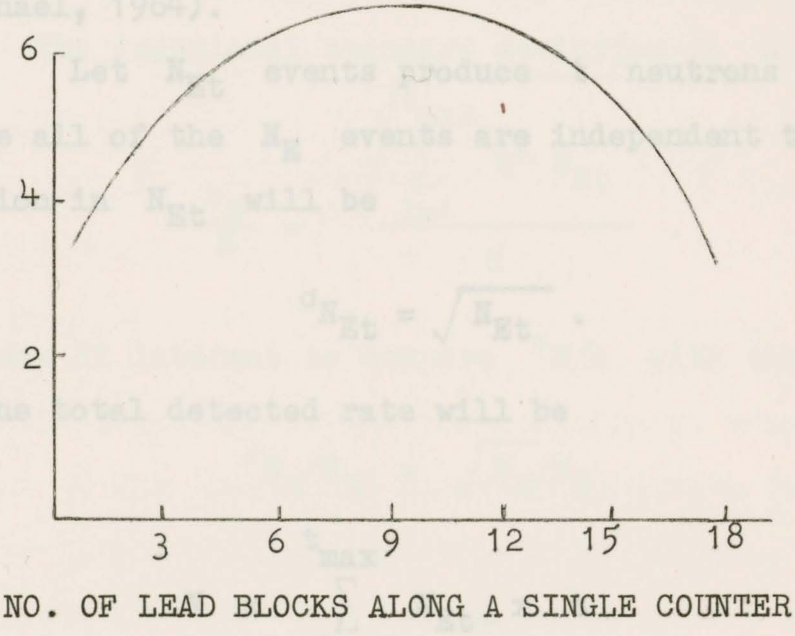


Fig. 3
Efficiency for detection as a function of position of disintegration in the monitor (Hatton and Carmichael, 1964).

---

[*] $<t>$ is the average number of evaporation neutrons produced per disintegration times the average efficiency.

statistics of N , the total detected 5 minute count rate. For the present it will be assumed that each detected neutron is counted, i.e. that there is no dead time and consequently no counting loss due to dead time. The effect of the dead time on the count rate will be discussed below.

The statistics of fluctuations in the five minute count can be examined by dividing the count into groups according to the detected multiplicity t (Hatton and Carmichael, 1964).

Let N_{Et} events produce t neutrons per event. Because all of the N_E events are independent the standard deviation in N_{Et} will be

$$\sigma_{N_{Et}} = \sqrt{N_{Et}} \; . \tag{3}$$

Also the total detected rate will be

$$N = \sum_{t=1}^{t_{max}} N_{Et} \times t \tag{4}$$

and the standard deviation σ_N , in N , will be*

---

*See for example Parratt, I.G. 1961, Probability and Experimental Errors in Science, John Wiley and Sons Inc., New York.

$$\sigma_N{}^2 = \sum_{t=1}^{t_{max}} (\partial N/\partial N_{Et})^2 \, \sigma_{N_{Et}}^2$$

$$= \sum_{t=1}^{t_{max}} t^2 \, N_{Et} \qquad (5)$$

on using equations (3) and (4). Since the number of detected events with multiplicities greater than ten is negligible, then one uses a value of t_{max} of about ten, both in theory and experiment (Hatton and Carmichael, 1964). The fractional standard deviation in N will be

$$\frac{\sigma_N}{N} = \frac{\sqrt{\sum_{t=1}^{t_{max}} t^2 \, N_{Et}}}{N} \; . \qquad (6)$$

It is now of interest to compare $^{\sigma}N/N$ with the quantities

$$^{\sigma}N_E/N_E = \sqrt{N_E}/N_E \qquad (7)$$

and

$$\sigma/N = \sqrt{N}/N \; . \qquad (8)$$

The ratio in equation (8) would be the fractional standard deviation in the detected count rate, if the fluctuations in this count rate could be described by Poisson statistics. Since

$$N_E = \sum_{t=1}^{t_{max}} N_{Et}$$

and

$$N = \sum_{t=1}^{t_{max}} t \times N_{Et}$$

then

$$\frac{\sigma_{N_E}}{N_E} = \frac{1}{\sqrt{\sum_{t=1}^{t_{max}} N_{Et}}} < \frac{\sigma_N}{N}$$

and

$$\frac{\sigma}{N} = \frac{1}{\sqrt{\sum_{t=1}^{t_{max}} t \times N_{Et}}} < \frac{\sigma_N}{N} .$$

The effect therefore of the multiplicity of evaporation neutrons on the fractional standard deviation is to increase this quantity. Hatton and Carmichael, 1964, showed that in fact ${}^{\sigma}N/N$ was a factor of 1.4 times greater than σ/N .

III. THE EFFECT OF COUNTER DEAD TIME ON THE DETECTED COUNT RATE AND ON THE STANDARD DEVIATION

Some of the neutrons from a burst of evaporation neutrons resulting from a single interaction in the lead may be captured in a counter very shortly after the event has occurred whereas some others may migrate for a period of time before being captured. The resulting series of neutron captures has an exponential time distribution (Hatton and Carmichael, 1964) similar to the decay of a radioactive element and has a mean lifetime τ associated with it. This mean lifetime has been calculated using diffusion theory (Pearce and Mason, 1966)*, and measured experimentally (Hatton and Carmichael, 1964) (see also section VI). It is of the order of 300 microseconds.

Four mean lifetimes after the first neutron of a burst is detected, 98% of the detected neutrons will have been captured. Therefore, if the counters are made insensitive by imposing an artificial dead time for a length of time 4τ after every detected pulse, only the nuclear disintegration is detected, i.e. the quantity N_E in section II.

---

*More than one mode is found in this paper but the maximum mean lifetime is of the order of 300 microseconds.

Therefore the analysis of the fluctuations in the count rate is considerably simplified (cf. equation (1) section II), and also the registered count rate is more meaningful with regard to interpretation of variations in the secondary cosmic ray flux. Since the N_E are random events, the simple correction formula

$$N_{E(\text{true})} = \frac{N_{E(\text{observed})}}{1 - N_{E(\text{observed})} \times \tau_D} \qquad (9)$$

can be applied to the observed data, where $N_{E(\text{true})}$ is the event rate after correction, $N_{E(\text{observed})}$ is the registered count rate, and τ_D is the dead time of the system. The dead time correction can be conveniently applied to the five minute count rates by incorporating it into a computer program.

The equipment used in this investigation is described in the next section.

IV. ELECTRONICS

(a) Overall System

The neutron capture reaction taking place is

$$B^{10} + N \longrightarrow Li^{7} + \alpha \ .$$

In approximately 94% of the reactions the Li^7 is left in the 480 keV excited state and 2.30 MeV appears as kinetic energy. In approximately 6% of the reactions the Li^7 goes directly to the ground state and 2.78 MeV is released (Fowler, 1963). Both the α particle and the recoiling lithium nucleus contribute to a relatively large ionization pulse.

The counters used in the NM-64 neutron monitor are built by Electronic Associates Limited* under supervision of Atomic Energy of Canada Limited. The operating voltage is -2900 volts, and the counters have the usual preamplifier and discriminator circuits.

The pulses from the counter amplifiers are fed into the dead time unit described in part (b) below. From the output of the dead time unit the pulses are fed into a RIDL† amplifier discriminator unit (Model 30-19)

---

*4616 Yonge Street, Willowdale, Ontario, Canada.

†Radiation Instrument Development Laboratory, 4501 W. North Avenue, Melrose Park, Illinois.

where they are further amplified before being fed via cables to the RIDL scalar (Model 49-44). The scalar accumulates for periods of five minutes. The accumulated five minute count rate is fed to a relay unit (AECL T6024 N-R-X) and then to a paper tape punch (IBM). At the end of each five minute period, as determined by a digital clock, the accumulated count, the universal time and the barometric pressure are punched onto paper tape suitable for conversion to punched cards for computer analysis. Fig. 4 shows the system as it was set up, with pulse characteristics displayed at points of interest.

(b) <u>The Dead Time Unit</u>

This unit consists of an integrated network of DEC* Flip Chip modules. Each of the outputs from the six counters is fed into a comparator which consists of a difference amplifier and a clamped diode gate (Fig. 5). This unit was designed to standardize the output pulses in amplitude but not in length. The length depends on the amplitude of the input pulses. The output from the W520 are -3.4V to ground square pulses. These are fed into a pulse amplifier and are mixed at the input of this unit (Fig. 6). The pulse amplifier standardizes the length of the pulses from the comparator and provides a standard 400 nanosecond -3.4V to ground square pulse.

---

*Digital Equipment Corporation, Maynard, Massachusetts.

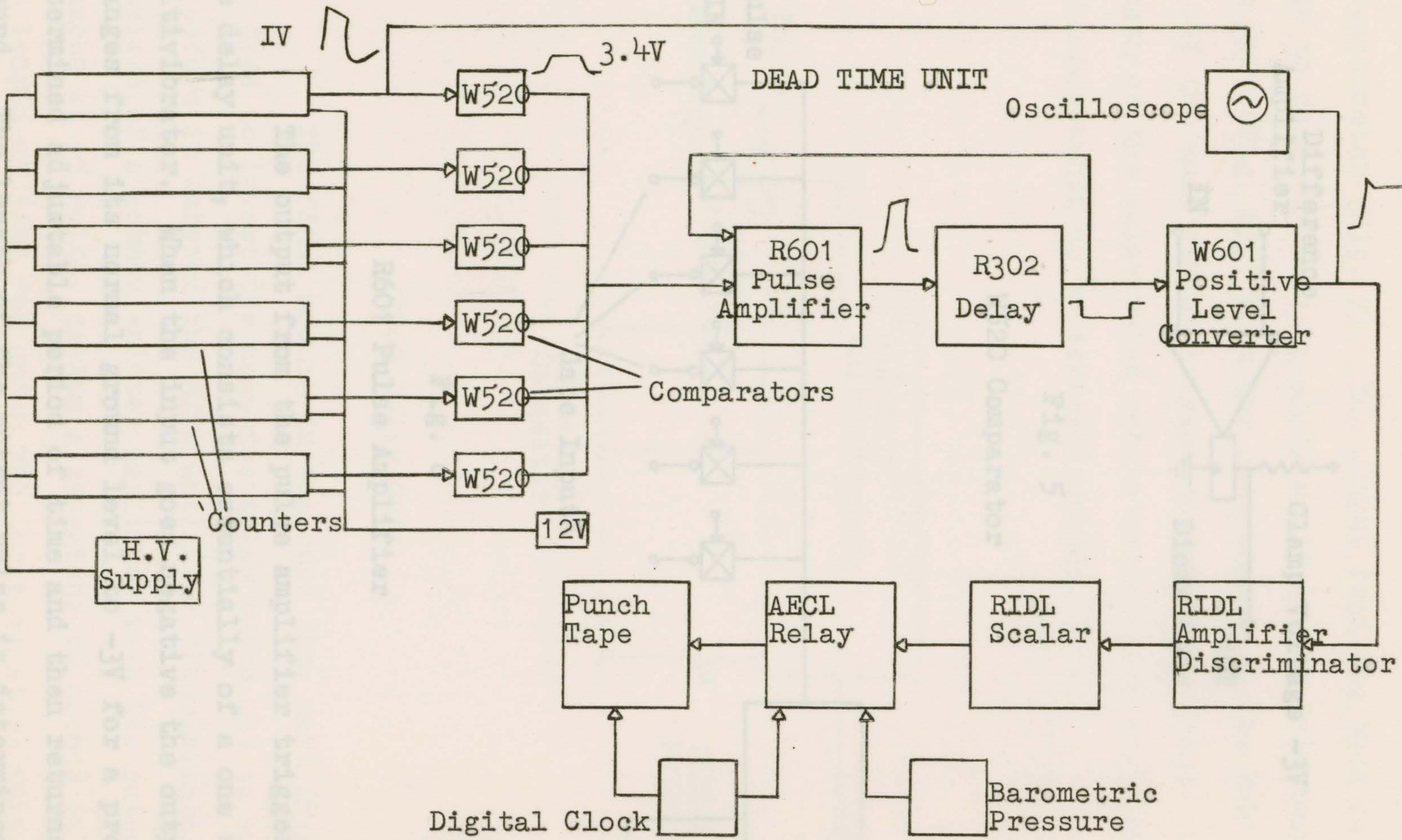


Fig. 4

Block diagram of the electronics used to examine the effect of varying the counter dead time on the standard deviation

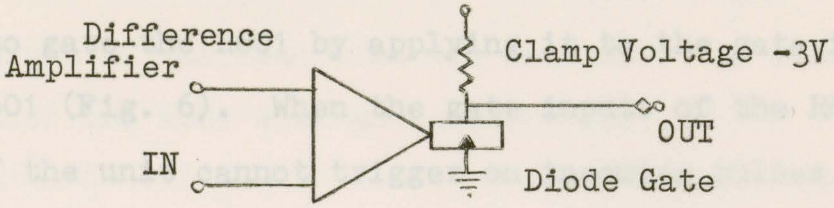


Fig. 5

W520 Comparator

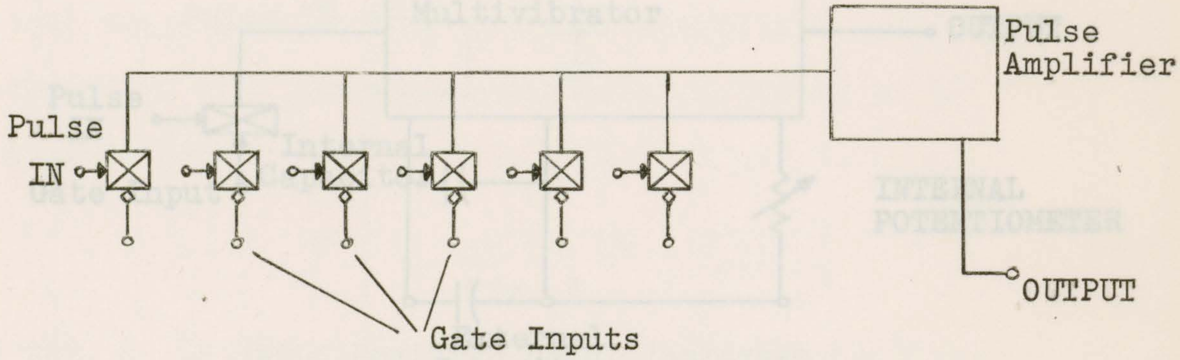


Fig. 6

R601 Pulse Amplifier

The output from the pulse amplifier triggers the delay unit, which consists essentially of a one shot multivibrator. When the input goes negative the output changes from its normal ground level to -3V for a predetermined adjustable period of time and then returns to ground. The length of the output pulse is determined by the internal and external capacitors, and by the internal potentiometer (Fig. 7). The output from the R302 is also used to gate the R601 by applying it to the gate inputs of the R601 (Fig. 6). When the gate inputs of the R601 are at -3V the unit cannot trigger on incoming pulses. The length of the delay pulse can be varied from a minimum of 400 nanoseconds up to several seconds.

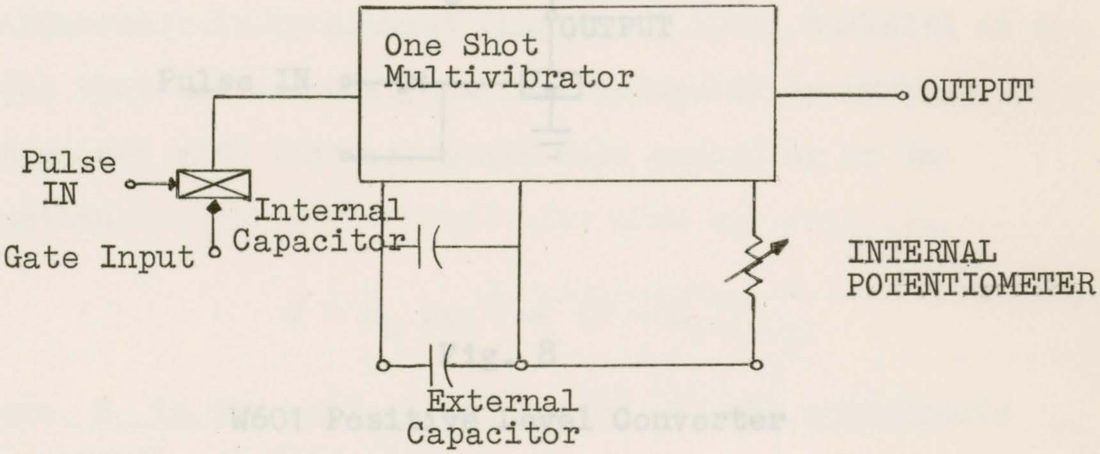


Fig. 7

R302 Delay Unit

The final module in the dead time unit (Fig. 8) was used to invert the negative delay pulse and to amplify it before it entered the RIDL amplifier discriminator. It consists of a common emitter amplifier with the output clamped at +5 volts, giving a resulting 5V output pulse for the length of time for which the input is at -3 volts. It is thus possible to trigger the complete unit on the first pulse of a burst of pulses and to have it insensitive to further incoming pulses for a desired length of time. The length of the dead time was determined by monitoring the output of the W601 with an oscilloscope.

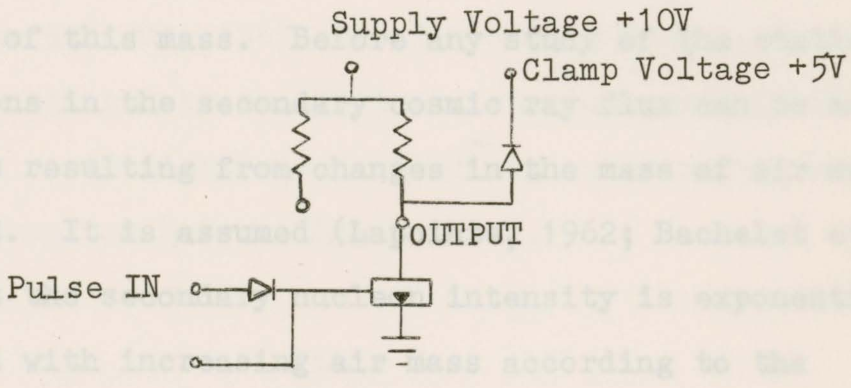


Fig. 8

W601 Positive Level Converter

V. PRESSURE CORRECTIONS TO THE NUCLEON INTENSITY

The cosmic ray intensity at a neutron monitor is a function of the mass of air above the monitor. The atmospheric pressure recorded at a station is taken as a measure of this mass. Before any study of the statistical fluctuations in the secondary cosmic ray flux can be made, variations resulting from changes in the mass of air must be removed. It is assumed (Lapointe, 1962; Bachelet et al, 1964) that the secondary nucleon intensity is exponentially attenuated with increasing air mass according to the equation

$$N = N_o \exp [-\alpha (P - P_o)] \quad (10)$$

where N is the nucleon intensity, P the atmospheric pressure, α the barometric coefficient and P_o is a standard pressure. N_o is the corrected count rate.

The procedure employed in the present work was to incorporate equation (10) into the computer program used to analyse the detected count rate (see Appendix I) and to correct each five minute accumulated value. Following standard procedure the pressure P_o was taken as 760 mm of Hg. The barometer used to measure the pressure was of the type recommended by the International Union of Pure and Applied Physics Sub Commission on Cosmic Ray

Intensity Variations (Carmichael, 1964) and supplied by Exactel Instrument Company[*]. It is a standard temperature-compensated mercury barometer with digital output giving the pressure in centimetres to four significant figures (0.01 cm of Hg). The barometric coefficient α used was the mean of the monthly barometric coefficients for the months June and July 1967 (see Table I) and was calculated from data obtained by the Victoria station. The monthly barometric coefficient was derived[†] by carrying out a linear regression between Log N and P.

Table I

Barometric Coefficient α for June and July 1967

	Month	
	June 1967	July 1967
Barometric coefficient per mm Hg	0.0106	0.00906

The mean barometric coefficient is, from Table I, 0.0098 ± 0.0011 per mm of Hg.

The uncertainty in the corrected count rate as a result of the uncertainty in α is of the order of 0.3%

---

[*] Exactel Instrument Co., 89 Alice Avenue, Mountain View, California.

[†] The data of Table I was made available by the Victoria cosmic ray station.

(see Appendix II). This uncertainty is somewhat less than the 1% uncertainty resulting from statistical fluctuations, and in any case the barometric coefficient should be relatively constant over the time for which the analysis of fluctuations is made; thus the 0.3% uncertainty was ignored in these analyses.

VI. EXPERIMENTAL RESULTS

(a) The mean lifetime of the evaporation neutrons in the monitor

The mean lifetime of the evaporation neutrons in the monitor was determined by measuring the counting rate as a function of dead time (Hatton and Carmichael, 1964). The dead time τ_D was varied from 20 microseconds to 1200 microseconds. The detected count rates were corrected for pressure fluctuations and for dead time before being plotted. The dead time correction was of the form of equation (9) but this is at best only approximate for dead times less than 1200 microseconds. However since an accurate value of the mean lifetime of the neutrons is not required this correction was assumed to be adequate.

The natural logarithm of excess detected neutrons $N(\tau_D) - N_{(1200)}$ plotted as a function of the dead time is a straight line (Fig. 9) from which the mean lifetime is estimated as 300 microseconds.

(b) Determination of the mean detected multiplicity <t>

The mean detected multiplicity is given by the equation

$$\langle t \rangle = N/N_E \qquad (11)$$

where N is the count rate corresponding to 20 microseconds

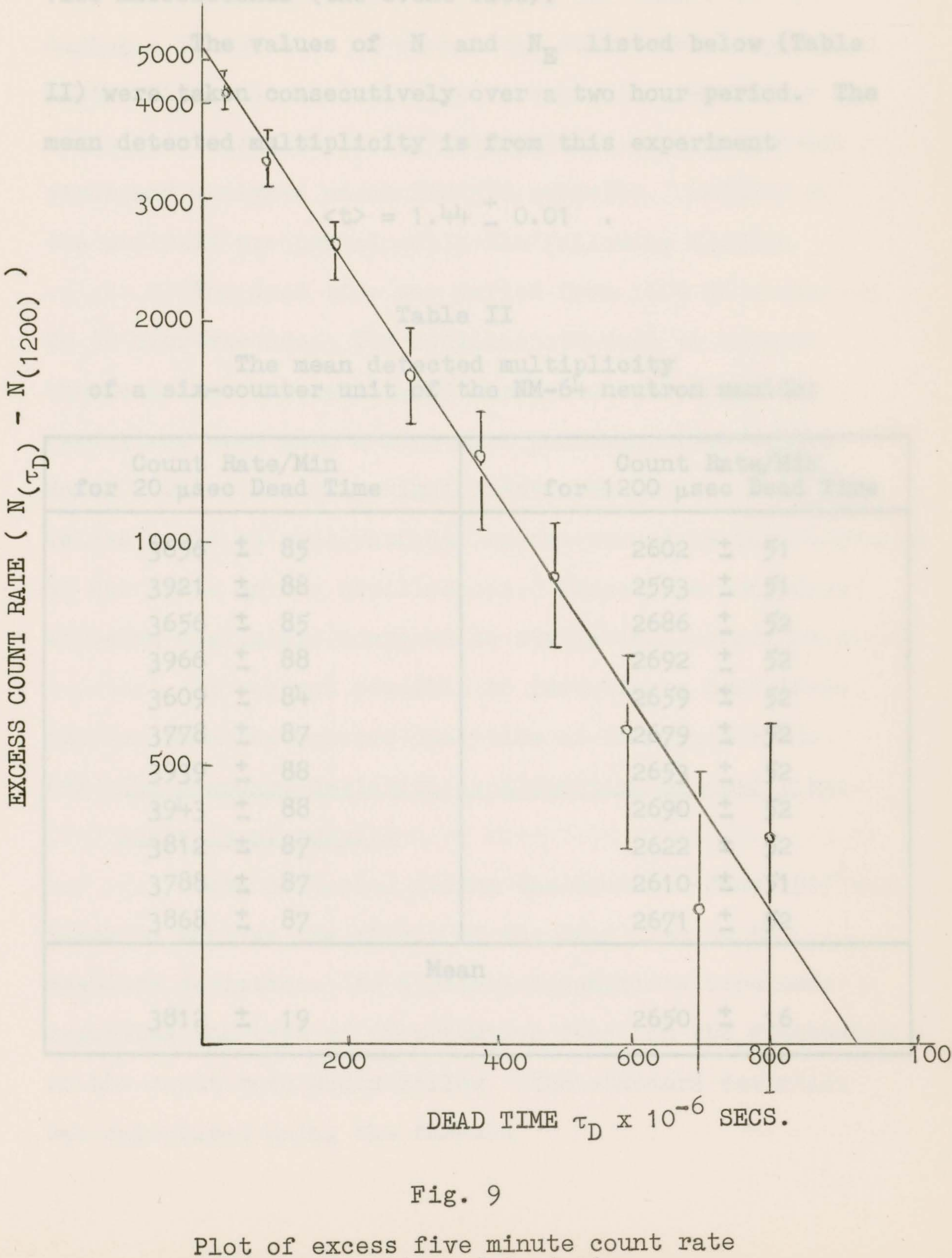


Fig. 9

Plot of excess five minute count rate
as a function of dead time.

dead time and N_E is the count rate corresponding to 1200 microseconds (the event rate).

The values of N and N_E listed below (Table II) were taken consecutively over a two hour period. The mean detected multiplicity is from this experiment

$$\langle t \rangle = 1.44 \pm 0.01 \quad .$$

Table II

The mean detected multiplicity
of a six-counter unit of the NM-64 neutron monitor

Count Rate/Min for 20 µsec Dead Time	Count Rate/Min for 1200 µsec Dead Time
3656 ± 85	2602 ± 51
3921 ± 88	2593 ± 51
3656 ± 85	2686 ± 52
3966 ± 88	2692 ± 52
3609 ± 84	2659 ± 52
3778 ± 87	2679 ± 52
3939 ± 88	2653 ± 52
3943 ± 88	2690 ± 52
3812 ± 87	2622 ± 52
3788 ± 87	2610 ± 51
3868 ± 87	2671 ± 52
Mean	
3812 ± 19	2650 ± 16

(c) The collection of data

Data was collected during the summer of 1967 during a period when no cosmic ray storms were registered at the Victoria station. The five minute accumulated count rate was transferred from punched tape to punched cards and analysed on an IBM 360 computer. Details of the analysis are contained in the following section.

The dead time was varied from 1200 microseconds to 50 microseconds. The oscilloscope used to measure the dead time was calibrated throughout the range of dead times used with a time mark generator (Tektronix, Model 180A). The only significant error in the dead time values could be observational errors caused by the thickness of the trace on the oscilloscope. These were considered as being negligible compared to statistical errors obtained.

It was not possible to investigate dead times shorter than the counter dead time of 20 microseconds.

(d) The standard deviation as a function of dead time: analysis of results

Data collected during the month of June 1967 was taken to analyse the effect of the dead time on the standard deviation. No a priori assumptions were made regarding the type of distribution function the fluctuations in the count rate would follow. The standard deviation was calculated using the formula

$$\sigma = \sqrt{\sum_{i=1}^{M} (N_i - \langle N \rangle)^2/M} \qquad (12)$$

where M is the number of five minute corrected counts taken in the analysis, <N> is the arithmetic mean of the corrected five minute count rate and N_i is the corrected five minute count rate for the i^{th} five minute interval.

Because of the diurnal variation in the corrected count rate it was decided to keep the range M as small as possible and yet large enough to make the calculated standard deviation statistically meaningful. On the basis of some preliminary experiments it was decided to calculate values of σ for a range of data covering a five hour period. This corresponded to $M = 60$ in equation (12) above.

Data which showed fluctuations large compared to the standard deviation calculated was rejected, these fluctuations being assumed to result from spurious cosmic ray events within the monitor and not an indication of the general statistical fluctuations encountered. The analysis thus was a double analysis, the first run on the computer being taken for all data. The results of this run were subsequently analysed and the initial raw data examined for fluctuations exceeding four times the standard deviation. If the initial data showed only very few such large fluctuations then just these values were removed and the remaining data treated as before. If however there were many such large fluctuations evident in the initial data the complete five hour period was rejected.

The results of the analysis on the data collected during the period June 16 - June 26, 1967 are contained in Fig. 10. The average standard deviation and fractional standard deviation are an arithmetic mean of as many values as possible, using the above procedure. Where only one value of the standard deviation was available the value was not plotted. The error bars in Fig. 10 were calculated by using the same formula as equation (12). The fractional standard deviation was calculated from $\sigma/\langle N\rangle$.

As can be seen from Fig. 10 there was an 18% improvement in the fractional standard deviation for the data of June when the dead time was increased from 50 microseconds to 1200 microseconds. A complete summary of the improvements in the standard deviation and fractional standard deviation are contained in Table III. It can be seen from this table that even for values of the dead time of 500 microseconds there is a significant improvement in the standard deviation and fractional standard deviation.

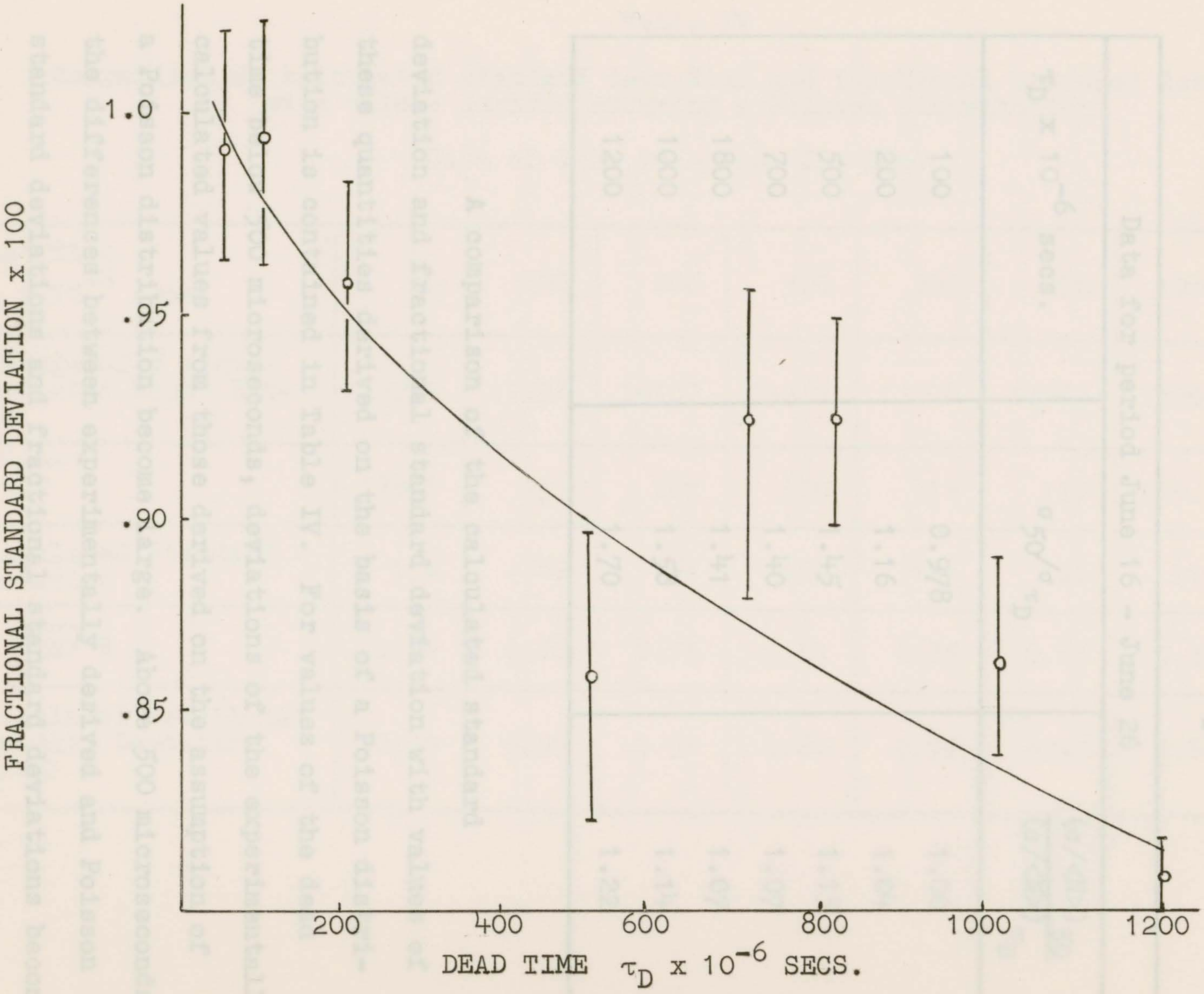


Fig. 10

Plot of fractional standard deviation as a function of dead time for the period June 16 - June 26, 1967

Table III

The standard deviation and fractional standard deviation for a dead time of 50 microseconds compared to the values for dead time τ_D

Data for period June 16 - June 26		
$\tau_D \times 10^{-6}$ secs.	$\sigma_{50}/\sigma_{\tau_D}$	$\frac{(\sigma/\langle N\rangle)_{50}}{(\sigma/\langle N\rangle)_{\tau_D}}$
100	0.978	1.00
200	1.16	1.04
500	1.45	1.15
700	1.40	1.07
1800	1.41	1.07
1000	1.58	1.14
1200	1.70	1.22

A comparison of the calculated standard deviation and fractional standard deviation with values of these quantities derived on the basis of a Poisson distribution is contained in Table IV. For values of the dead time below 500 microseconds, deviations of the experimentally calculated values from those derived on the assumption of a Poisson distribution become large. Above 500 microseconds the differences between experimentally derived and Poisson standard deviations and fractional standard deviations becomes quite small. In particular at 1000 microseconds these quantities are very nearly equal.

Table IV

Comparison of calculated standard deviation and fractional standard deviation with values derived assuming a Poisson distribution

Data of June 16 - June 26, 1967

Dead Time $\tau_D \times 10^{-6}$ secs	50	100	200	500	700	800	1000	1200
Average of 5 minute Corrected Count Rate $\langle N \rangle$	17992	17238	16107	14359	13828	13663	13060	12918
$\sqrt{\langle N \rangle}$	134.1	131	127	120	118	117	114.3	113.6
Calculated Standard Deviation σ	178	182	154	124	126	126	112	105
$1/\sqrt{\langle N \rangle}$ %	0.74	0.76	0.78	0.83	0.85	0.85	0.87	0.87
Calculated Fractional Standard Deviation $\sigma_N/\langle N \rangle$ %	0.99	0.99	0.96	0.86	0.92	0.92	0.86	0.81

VII. DISCUSSIONS AND CONCLUSIONS

The results of the analysis provide a strong argument for using a value of the counter dead time of 1200 microseconds in NM-64 neutron monitors. In the type of research normally done with a neutron monitor, that of examining small variations in the secondary intensity, the margin for error should be kept to a minimum. On the basis of the foregoing results it would seem that using short dead times introduces an unnecessarily large error in the count rate. Clearly this is a most undesirable complication to add to any analysis of the secondary count rate. The decrease in the count rate when using a 1200 microsecond dead time does not constitute a serious drawback. Rather does it make the count rate registered more closely related to the actual interacting component of the secondary cosmic rays. It also allows an exact dead time correction formula to be used, something which is not possible for dead times less than 1200 microseconds.

A dead time unit similar to the one used in this work does not involve large modifications to present equipment and once built can be incorporated into most systems without difficulty. The total cost of the dead time unit is of the order of $400 and provides an inexpensive and useful addition to the NM-64.

BIBLIOGRAPHY

Bachelet, F., Balata, P., Dyring, E., Iucci, N., Villaresi, G., Unpublished.

Bercovitch, M., Carmichael, H., Hanna, G. C., Hincks, E. P., Phys. Rev., 119, 412, 1960.

Carmichael, H., IQSY Instruction Manual No. 7, IQSY Secretariat, 1964.

Cocconi, G., Cocconi Tongiorgi, V., Widgoff, M., Phys. Rev., 79, 768, 1950.

Davila Apointe, J., Karff, S. A., Rev. Sci. Instr., 31, 532, 1959.

Dostrovsky, I., Rabinowitz, P., Bivins, R., Phys. Rev., 111, 1659, 1958.

Fowler, I. L., Rev. Sci. Instr., 34, 731, 1963.

Geiger, G., Can. Journ. Phys., 34, 288, 1956.

Harman, C. V., Hatton, C. J., Unpublished.

Hatton, C. J., Carmichael, H., Can. Jour. Phys., 42, 2443, 1964.

Hughes, E. B., Marsden, P. L., Brooke, G., Meyer, M. A., Wolfendale, A. W., Proc. Phys. Soc., 83, 239, 1964.

Janossy, L., Theory and Practise of the Evaluation of Measurements, Oxford Press, 1965.

Lapointe, S. M., Rose, D. C., Can. Jour. Phys., 40, 687, 1962.

Metropolis, N., Bivins, R., Storm, M., Friedlander, G., Phys. Rev., 110, 204, 1958.

Pearce, R. M., Fowler, A. G., Jour. Geophys. Research, 69, 4451, 1964.

Pearce, R. M., Mason, G. R., Il Nuovo Cimento, 45, 1030, 1966.

Serber, R., Phys. Rev., 72, 1114, 1947.

Simpson, J. A., Fonger, W., Treiman, S. B., Phys. Rev., 90, 934, 1953.

APPENDIX I

Computer Program Used to Pressure Correct the Count Rate and to Evaluate the Standard Deviation and Fractional Standard Deviation

```
C  STATISTICAL ANALYSIS OF A SIX COUNTER UNIT OF THE NM-64

C

C P.  COUGHLAN   PHYSICS DEPARTMENT

C  READ SCALAR B ONLY CORRECT COUNTS, PRINT PAGE HEADING

                  WRITE (6,120)
         10       SUM = 0.
                  SUMS Q=0
                  N=0
         15       READ (5,110) IDT, IGE,ID,IM
         20       READ (5,100) PX,X,PY,Y, PZ,Z
                  Z=Z*EXP((PZ-760.)/101.73)
                  IF(Z)40,40,30
         30       SUM=SUM+Z
                  SUMSQ=SUMSQ+Z*Z
                  N=N+1
         40       Y=Y*EXP((PY-760.)/101.73)
                  IF(Y)60,60,50
         50       SUM=SUM+Y
                  SUMSQ=SUMSQ+Y*Y
                  N=N+1
         60       X=X*EXP((PX-760.)/101.73)
                  IF(X)80,80,70
         70       SUM=SUM+X
                  SUMSQ=SUMSQ+X*X
                  N=N+1

                  GO TO 20

C

C  CALCULATE AVERAGE, STANDARD DEVIATION, FRACTIONAL STANDARD
   DEVIATION

C
```

```
80      AN=N
        AV=SUM/AN
        SD=SQRT(SUMSQ/AN-AV*AV)
        FRSD=SD/AV
        WRITE(6,130)AN,AV,SD,FRSD,IDT,IGE,ID,IM
100     FORMAT(6X,F4.1,6X,F6.0,10X,F4.1,6X,F6.0,10X,
          F4.1,6X,F6.0,6X)
110     FORMAT(14,A1,212)

1200    FORMAT('1','NO.OF',5X,'AVERAGE OF ',3X,
          'STANDARD',3X,'FRACTIONAL',13X,'DEAD
          TIME',3X,'GEOMETRY',2X,'DAY','MONTH'/
          'EVENTS',5X,'CORRECTED ',4X,DEVIATION',
          2X,'STANDARD',8X,'IN',8X,'CODE'/3X,
          'N',8X,'COUNT  RATE',14X,'DEVIATION',
          4X,'MICROSECS',3X,'LETTER')

C
1300    FORMAT(1HO,F3.0,6X,IPe11.4,2X,IPE10.3,1X,
          IPE11.4,4X,14,9X,A1,6X,121,3X,12)

        GO TO 10

        END
```

APPENDIX II

The Effect of Uncertainties in the Barometric Coefficient on the Pressure Corrected Count Rate

The pressure correction to the count rate is given by

$$No = N \exp [\, \alpha \, (P - Po)] \qquad (13)$$

where No is the corrected count rate referred to the standard pressure Po, N is the count rate at pressure P and α is the barometric coefficient. To obtain the uncertainty ΔNo in No due to the uncertainty $\Delta\alpha$ in α, equation (13) is differentiated at constant P giving

$$\Delta No = (P - Po)\, No\, \Delta\alpha$$

$$\text{or} \quad \frac{\Delta No}{No} = (P - Po)\, \Delta\alpha \qquad (14)$$

$$\Delta\alpha = 0.0011 \text{ (see section V)}$$

$$Po = 760 \text{ mm Hg}$$

The average pressure during June - July 1967 is 757 mm Hg.

Equation (14) thus gives a value for $\Delta No/No$ of

$$\frac{\Delta No}{No} = 0.0033$$

on substituting the above values of Po, P and α in (14).

This uncertainty in the corrected count rate has been taken as being negligible.

APPENDIX III

Stability of the Monitor

(i) Atmospheric temperature

It has been tacitly assumed in the theory that the neutrons detected in the monitor counters resulted only from nucleon interactions within the monitor. However approximately 4% of the detected counts are a result of muon and pion interactions in the monitor (Harman and Hatton, 1967). The intensity recorded by the monitor therefore depends on the distribution of mass above it because of the decay of the mesons in the cascade. This mass distribution is a function of temperature changes in the atmosphere and as a result the recorded intensity is a function of the atmospheric temperature.

The above authors have shown that this temperature effect results in a correction factor which varies over the year but which has a value of the order of 0.2% for the months June and July.

No data was available for the distribution of temperatures above the Victoria Station and no correction was therefore attempted.

(ii) Neutrons from outside the monitor

Only neutrons which originate in the monitor are of interest and hence account has to be taken of neutrons which originate outside the monitor and penetrate the three inch outer reflector. These will consist generally of fast evaporation neutrons resulting from cosmic ray secondary interactions outside the monitor. An analysis of the effect of this background has been carried out by Hatton and Carmichael, 1964, and their results have been taken as applying to the monitor at Victoria. They found that the three inch reflector thickness the background constituted 5.5% of the total detected count rate. The raw data is not usually corrected for this effect before being analysed. Second order effects resulting from further evaporation neutrons being produced in the polyethylene by these fast "outside" neutrons are also neglected. The background counting rate arising from natural alpha active contamination of the steel walls of the counters is quoted by the above authors as being less than 1% of the cosmic ray intensity and so this is also usually neglected in correcting the raw data.

(iii) <u>The counters</u>

Any impurities in the gas of the boron trifluoride counters will have an adverse effect on the counting rate. The net effect on the counters is a reduction in the pulse size (Davila Apointe and Korff, 1959). This reduction in pulse size will show up as a spread in the pulse height distribution curves of the counters and so these distributions have been taken as an indication of any large impurities in the counter gas. The expected pulse height distribution curves of the counters should, if the disintegration products (Li^7 and an α particle) give up their energy quantitatively in ionization of the gas and if all electrons produced were collected simultaneously, show only two sharp pulses corresponding to 2.30 and 2.78 MeV energies. One of these (corresponding to the 2.30 MeV energy) should dominate since the reaction which yields this energy of Li^7 occurs in 94% of the cases. It is over the region of the pulse height distribution curve corresponding to this reaction that the counters were examined.

There will be a finite spread in the pulse height for the 2.30 MeV Li^7 energy resulting from statistical fluctuations in the number of electrons formed and statistical fluctuations in the gas amplification factor. This effect is not expected to contribute more than 20% spread in the pulse width at half the maximum height (Fowler 1963). Thus the criterion invoked in the analysis of the counter gas purity was that the full width at half maximum of the pulse distribution be less than 20%. The six counters were analysed and were found to be operating within this criterion.

As a further check on the operation of the counters a plateau check was carried out. The plateaus of all counters are quite flat in the region of the operating voltage (-2900 V) and satisfy the criterion of the slope being less than 2% per 100 volts in this region (Carmichael, 2, 1964).

It was shown by Hatton and Carmichael, 1964, that an increase of 50V in the counter voltage did affect the dead time of the counters by 1 microsecond but that this resulted in a negligible small (0.05%) fractional decrease in the count rate.

In view of the results of the above analysis no corrections were deemed necessary for counter gas impurities or drift in the high voltage.

(iv) Local temperature changes

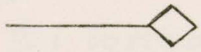
The effect of local temperature changes on the counting rate as a result of changes of counter gas pressure with temperature was assumed to be of the same order as that derived by Simpson et al, 1953. They found that the local temperature coefficient was of the order of 0.04% per degree Centigrade, and this was assumed to have negligible effect on the counting rate compared to the statistical fluctuations under examination.

APPENDIX IV

Glossary of Logic Symbols for Section IV and Circuit Diagram for Counter Amplifier

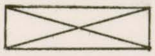
Glossary of logic diagram symbols

Pulse input



Normally at ground level

Inverter



Diode capacitor gate

Surname: COUGHLAN Given Names: PADRAIG AUSTIN

Place of Birth: DUBLIN, IRELAND Date of Birth: 24/9/1941

Educational Institutions Attended, with Dates of Entering and Leaving:

ST. JOSEPH'S SCHOOL, FAIRVIEW, DUBLIN	1945 to 1959
UNIVERSITY COLLEGE, DUBLIN	1959 to 1963
UNIVERSITY OF VICTORIA, VICTORIA	1965 to 1967

Degrees, Diplomas, Etc., Awarded, with Dates and Names of Institutions:

B.Sc.	October 1963	University College, Dublin

Honors and Awards:

University of Victoria Graduate Bursary

Publications:

THE UNIVERSITY OF VICTORIA LIBRARY

MANUSCRIPT THESIS

AUTHORITY TO DISTRIBUTE

AUTHOR: This thesis may be lent or microfilm copies made available:

(signature of the author

[redacted]

(a) Without restriction

(b) With the restriction that, for a period of five years

(until . . . .) the

written approval of the following is required:

(1) The Dean, Faculty of Graduate Studies . . . .

(2) The Author . . . .

(3) both the Dean, Faculty of Graduate Studies, and the Author . . . .

BORROWERS: The borrower undertakes, by signing below, to give proper credit for any use made of the thesis, and to obtain the consent of the author if it is proposed to make extensive quotations, or to reproduce the thesis in whole or in part.

Signature of Borrower	Address	Date